Insulated Solar Electric Cooker with Phase Change Thermal Storage Medium

Final Design Review Report

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Abstract

This final design review document outlines the senior design project carried out by a team of four mechanical engineering students at the California Polytechnic State University – San Luis Obispo under the sponsorship of Dr. Peter Schwartz of the Cal Poly Physics department. The aim of this project was to improve upon the design of previously developed Insulated Solar Electric Cookers (ISECs) by adding a thermal storage system to allow for quicker cook times and the ability to cook food at non-peak solar hours. The team's goal was to develop a working prototype utilizing a phase change medium as the thermal storage system by the end of the 1-year project that would be tested against other contemporary, inexpensive cooking systems. The team was able to successfully design, manufacture, and test two functioning prototypes. The final design utilized diodes connected to a solar panel as the heating element due to their extremely low cost as well as their thermal properties. The phase change material selected for thermal storage was a sugar alcohol known as erythritol. The final prototype could boil 1 liter of water in under 20 minutes with a device efficiency of 35% and continued to store energy for over 4 hours. As a result, the ISEC with thermal storage exceeded or met all but one of the design requirements as it was unable to completely melt the erythritol in the allotted time. A discussion of these successes and possible solutions to this shortcoming are also discussed within this report. This document presents the summation of the team's work on the project from the project scope to the finished results and the process used to achieve these results. This document has been presented to Dr. Schwartz for review and approval.

Table of Contents

Table of Figures

1.0 Introduction

Access to electricity and its accompanying amenities is limited in developing countries throughout the world and is a large contributor to poverty and poor quality of life in these areas. In a joint effort to solve this problem, Dr. Peter Schwartz of the Physics Department at the California Polytechnic State University – San Luis Obispo (Cal Poly SLO) partnered with Dr. Robert Van Buskirk of "*Kuyere!*", a foundation dedicated to bringing electricity to the poorest rural communities in Africa. Dr Schwartz and Dr. Van Buskirk, with the help of several student research and design groups, have recently developed an Insulated Solar Electric Cooker (ISEC) for deployment in Africa. An ISEC is a simple cooking device, surrounded by insulation to minimize heat loss, that utilizes a diode chain heating element directly connected to a solar panel. These ISECs allow rural communities to reduce dependency on biomass fuels and their effects on health and the environment while gaining access to affordable electricity.

After receiving feedback from users of these ISECs, Dr. Schwartz and Dr. Van Buskirk determined that the addition of a thermal storage system was a necessary improvement to the device. This would allow the appliances to cook food faster and operate during times without direct sunlight. Dr. Schwartz, acting as a project sponsor, sought the assistance of a senior project team from the Mechanical Engineering Department at Cal Poly SLO for the design and implementation of this thermal storage system. This team was made up of four mechanical engineering students: Nate Christler, Marcus Strutz, Justin Unger, and Matthew Weeman. What follows is a detailed review of the background research conducted by the team, the design objectives derived from that background research that define the scope of the project, the team's preliminary concept design for the cooker, the plan and process for meeting the design objectives, the manufacturing process, the cost, the testing of the first device, the improvements between the first prototype and the second, the manufacturing of the second prototype, the testing and results from the final prototype, and the conclusions of the team and suggestions for future work.

2.0 Background

The first step in understanding the task at hand was researching background information pertinent to the project. This included research on customers, related products, and technical information related to solar cookers and thermal storage. Because the end customers are abroad with limited means of contact, most of the customer research came from Dr. Schwartz and Dr. Van Buskirk. The team felt confident in their ability to accurately represent the wants and needs of the developing communities that are the target of this project. The team split up research responsibilities between products and technical research in order to benchmark values for similar solar cookers and find appropriate materials for our application, respectively.

2.1 Customer Needs

The ISEC with thermal storage will ultimately be used by families in developing countries that do not have access to modern electrical grids. Unfortunately, the team was unable to interview these end customers directly. As a result, customer information and needs were inferred from Dr. Schwartz and Dr. Van Buskirk's expertise and the information available on the "*Kuyere!*" website [1]. Through communication with the project sponsor, the team determined that the most important goal of the project was to decrease the required cook time of meals within the ISEC to make the overall system more convenient for the end users. The previous ISEC heats the food directly with electricity collected from sunlight and has no means of storing heat or energy [2]. This limits the power of the ISEC to that of the photovoltaic panel and limits the cooking hours to daytime only. This may not appeal to the customer as they have the potential to cook food faster with their current method and may choose to continue doing so if a more effective ISEC is not designed.

For the customer to even consider using a new cooking device, like the ISEC, it must be comparable to the current method of food preparation. The addition of a thermal storage system is intended to accomplish that by increasing heat transfer rate to the food. This allows the ISEC to 'charge' throughout the day which would not only allow for expanded cooking hours but cook food faster as well. Here the word charge is used to signify the thermal storage medium absorbing and storing heat throughout the day. The added thermal mass will convert the solar cooker from a slow cooker to more of a traditional stovetop cooker.

Another essential aspect of this project was for the cooker to be inexpensive. Most of the targeted users for an ISEC have extremely limited economic means and cannot afford an expensive solar cooker. The goal of this project was to develop a cooker that can be manufactured for rural areas by its residents, so cost remained at the forefront of considerations throughout the design and production. The less our ISEC costs to produce, the larger the customer base this product can reach and more people it can positively impact. A secondary goal is to add the ability to charge other small electronics from the cooker. This function can be added to the existing diode chain, only necessitating configuration and interface changes.

With this new cooking technology, one thing that the team is keeping in mind throughout this design is that it may not be a complete overhaul of the customer's current food cooking process. A reasonably expected scenario is that the updated ISEC using thermal storage will be added to our customer's options for cooking. The project's goal is to strive to make this new technology desirable for years to come not just the present.

2.2 Related Products

One important aspect of this project to mention is that the ISEC with thermal storage will not be the first insulated solar electric cooker. Members of the physics research team working under Dr. Schwartz have been working on similar products for the past few years. This design is an improvement on the existing ISEC design. This is not the first iteration of it by any means. The research, information, and understanding that the other individuals who have worked and experimented with similar products to the ISEC is invaluable and must be thoroughly analyzed. Listed in the following sections are a few products relevant to the success of the phase change thermal storage project.

2.2.1 ISEC

In 2015, Cal Poly SLO students under the sponsorship of Dr. Schwartz set out to develop low cost energy-efficient Insulated Solar Electric Cookers (ISECs). The goal of their ISEC project was "to develop the appropriate cooking technology by the time the price of solar panels is low enough to make (insulated solar electric cooking) the best cooking option (within developing communities)" [2]. As the project team states, there are only three basic components to an ISEC: a solar panel, an electric heating element, and insulation. Despite the rapidly decreasing price of solar electricity, the most expensive component of an ISEC system is the solar panel. While a solar panel can be bought for under $1 per Watt, traditional (non-insulated) cooking requires power on the order of magnitude of 1000 Watts which would require a solar panel costing around $800, making such a system prohibitively expensive to the communities these systems are designed for [2]. With proper insulation to minimize energy loss, food can be slow cooked over the course of the day using a power supply of only around 100 Watts [2]. With this design in mind the project team developed several working ISEC prototypes.

One of the team's prototypes was a barbeque style cooker consisting of a 5-gallon steel drum cooking chamber with a heating element attached to the lid surrounded by insulation. Another prototype was a boil and simmer style insulated cooking pot. This prototype utilized a heater directly under a cooking pot filled with food and water which was surrounded by insulation. The team also developed a variant of the boil and simmer style prototype which utilized an immersion heater placed directly into the pot to heat its contents [2]. The team performed multiple tests on their ISEC prototypes to analyze their thermal efficiency and cooking ability. Part of the team went on a trip to Gulu, in Northern Uganda where they built and implemented two boil and simmer style ISEC units. The ISECs were built using only materials purchased in Gulu for a cost of only $110 per unit [2]. A photo of one of the ISEC units is shown in Figure 1. The ISECs are occasionally used to cook vegetables over shorter periods of times and larger meals such as beans over the course of the day, but the villagers will often still burn biomass rather than use ISECs [2].

Figure 1: ISEC implemented in Uganda. The outer structure is made of reed mat and rice hull are used as insulation. The heater rests inside a larger pot and a smaller pot holding food rest on top the heater. A ceramic tile is placed under the larger pot to insulate rice hulls from the hot spot under the heater. [2]

2.2.2 ISEC with Thermal Storage

In 2017, another team of three Cal Poly SLO mechanical engineering students attempted to implement a thermal storage system into an insulated solar electric cooker. The team's design consisted of three parts: a thermal storage reservoir, a heating element, and insulation. For the thermal storage reservoir, the team used a ten-pound cylindrical core of concrete, for the heating element, the team used nichrome wire embedded in the concrete core, and for the insulation, the team used rice hulls [3]. The team constructed a total of three prototypes. An assembly model of the team's first prototype can be seen in Figure 2. The team's first prototype was unsuccessful and started several fires. The team investigated these fires and found they likely resulted from a combination of two factors. First, part of the nichrome wire was not fully embedded in the concrete and exposed directly to the rice hull insulation and secondly, the rice hulls they were using as insulation tend to smolder well below their ignition temperature [3].

The team also found that the prototype displayed very uneven heating and that some points of the concrete reached temperatures of 680°F. The team took this into account when building their second prototype which incorporated commercial fiberglass insulation around the concrete core to shield the flammable rice hulls from potential hotspots. Their second prototype failed when one of the copper wires connecting the heating element melted due to excessive heat [3]. The team's final prototype was built and designed using greater care and they were able to successfully test it without any fires or failures. The prototype ultimately failed to meet their design goals and performed worse than the original ISEC. The final iteration was unable to bring 1 liter of water to a boil over a 3-hour period and therefore lacked the power to be a practical cooker [3]. While this senior project ultimately failed to produce a practical cooker, it still provides a great baseline of knowledge to work from for this design.

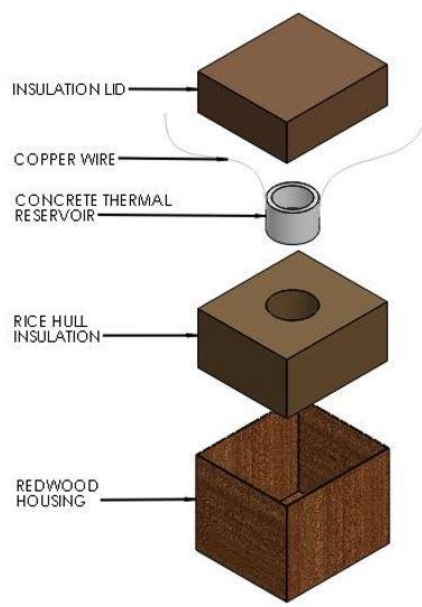


Figure 2. Assembly model of the initial ISEC prototype with thermal storage tested. [3]

2.2.3 Domestic Electric cum Solar Oven

Another similar product we found is a "Domestic Electric cum Solar Oven" developed in Pakistan in 2013 for renewable energy cooking. It is a circular oven with a heating element at the bottom used to increase the internal temperature. The oven utilizes reflectors to increase the amount of solar irradiation reaching the oven and solar panel as well as black paint to increase irradiation in the oven [4]. This oven does not have the same solar capacity as what we are targeting and is focused on supplementing cooking with solar power, so it uses an external electricity source as well. Our goal is to have an efficient and effective solar cooker powered completely by the sun. One aspect to think about from this design is the use of a thermostat. The addition of temperature regulation can mitigate the possibility of failure due to overheating and other important safety concerns. Other considerations brought to light from this project include the effects of ambient air temperature, relative humidity, and wind speeds in areas where this cooker will be used.

2.2.4 Solar Box Cooker with PCM Thermal Storage

We also found a report on the design and testing of a solar box cooker with thermal storage completed at an Italian university in early 2018. In this case, the thermal storage medium is a phase change material (PCM) that consists of a ternary mixture of nitrite and nitrate salts ($KNO3$, $NaNO2$, $NaNO3$). PCMs store energy in the form of latent heat and thus a high heat of fusion is advantageous. Throughout the day, energy from the solar panel transfers to the PCM to melt or evaporate the substance and store the energy for later use. The configuration of the cooker is very similar to ours, making use of concentric pots with the PCM occupying the space between them. This configuration fastens the two pots with four through bolts at the top, near the lid, spaced evenly around the circle. This design also uses aluminum fins between the two concentric pots to increase the heat transfer rate through the PCM [5]. The main difference between this cooker and our design will be the operating temperature, as solar salts are good for temperatures above 150 °C. In order to exceed these temperatures with solar panels, the design included multiple reflectors around the top to increase irradiation and fins to increase heat transfer. Through temperature testing in cookers with and without the thermal PCM, they found the cooling time of cookers that included PCM to last between 65% and 108% longer in the cooking temperature range [5].

2.2.5 Evacuated Tube Solar Cooker with PCM

In 2004, Japanese university students developed a solar cooker using evacuated tube solar heat (ETSH). These solar panels are a collection of small, insulated tubes that transfer heat to a liquid being pumped through the tubes, namely water. The heat is then transferred to the PCM, in this case a food additive called erythritol that has been used in artificial sweeteners. The solar cooker we are developing will use conventional PV panels rather than evacuated tube solar as the energy source, but this project provides good information on PCMs. Erythritol is non-toxic artificial sweetener with no known side effects, so food contamination would not be harmful, but should still be avoided. Erythritol also has a melting temperature of about 118 °C and a heat of fusion of about 340 kJ/kg. The results from cooking with ETSH and erythritol reveal it is possible to cook twice in one day, in the noon and in the evening [6]. Furthermore, the noon cooking has no effect on the later evening cooking [6]. These aforementioned characteristics, as well as the $1-3 per kilogram price tag make erythritol a viable PCM for our application.

2.3 Relevant Patents

2.3.1 Multifunctional Day and Night Solar Cooker Chinese Patent CN201811449U [7]

In this patent, the utility model relates to a multifunctional day and night solar cooker comprising a heat collector which not only comprises a heat-absorbing body and a heat pipe, but also increases a heat storage body and uses a light-gathering device. It also uses an internal light-gathering vacuum pipe heat collector or a vacuum pipe heat collector, the heat collector is connected to a heat storage tank and a non-return valve or a manual valve, and the multifunctional day and night solar cooker further increases the storage of a photoelectric cell.

2.3.2 Solar Induction Cooker Chinese Patent CN201983309U [8]

In this patent, the solar cooker is composed of a panel, a heating element, a heat insulation clapboard, a power supply layer and a base board. The solar cell module is electrically connected with the heating element and the power supply layer through wires to form a heating control system.

2.3.3 High efficiency low cost high precision automatic tracking solar furnace Chinese Patent CN2699194Y [9]

In this patent, the solar cooker accomplishes precise sun tracking through controlling the motor by a magnetic controlling circuit and adjusting the utility model by two axes, a longitudinal axis and a transverse axis. If an addition to the solar cooker using tracking device to benefit the efficiency was considered, this would be a main area of academia.

2.3.4 Solar powered cooker and/or heater with heat energy storage Patent DE4338736A [10]

In this patent, the cooker or heater is connected to a solar energy absorber and with a cooking and/or roasting system thermally, for heat energy transmission. The heat energy storage has a core of concrete or similar material. The cooking and roasting system is fitted on one side of the core.

2.3.5 Portable Solar/Non-Solar Cooker Patent US4203427A [11]

In this patent, the cooker using an oven compartment with insulated housing as well as having a removable portion of the body. This may be beneficial to our project if modifications to the outside body and insulation are a promising direction to take the solar cooker.

2.4 Technical Research

There were two areas of focus for technical research. First and foremost, the team needed to understand the new diode chain heating apparatus being implemented in this iteration of ISECs with thermal storage. With an understanding of how the diode chain functions, potential thermal storage systems were then researched.

2.4.1 Diodes

The most recent ISEC designs from Dr. Schwartz' research team have utilized a chain of diodes as the heating element, namely 1N5408 rectifier diodes. The research team decided to utilize more complex diode chains instead of simple nichrome wire primarily due to the unique current-voltage curve associated with diode chains. Diode chains exhibit near constant voltage over a wide range of current and if the chains are designed correctly to match their photovoltaic cell, they will operate near optimal efficiency regardless of solar intensity (which varies with the time of day and cloud conditions). Resistors, on the other hand, which linearly relate current and voltage can only be optimized for a single solar intensity level [12]. Figure 3 clearly shows this relationship.

IN5408 rectifier diodes were chosen due to their low cost (less than $0.05 per diode) and their thermal properties. The diodes have a rated operational temperature of up to 150 °C. Although earlier testing conducted by research students working in collaboration with Dr. Schwartz indicate 1N5408 rectifier diodes can be operational at temperatures up to 250 °C [12]. Regardless, the surrounding medium must be thermally conductive in order to keep the diodes cool and the PCM hot to create a more efficient cooker.

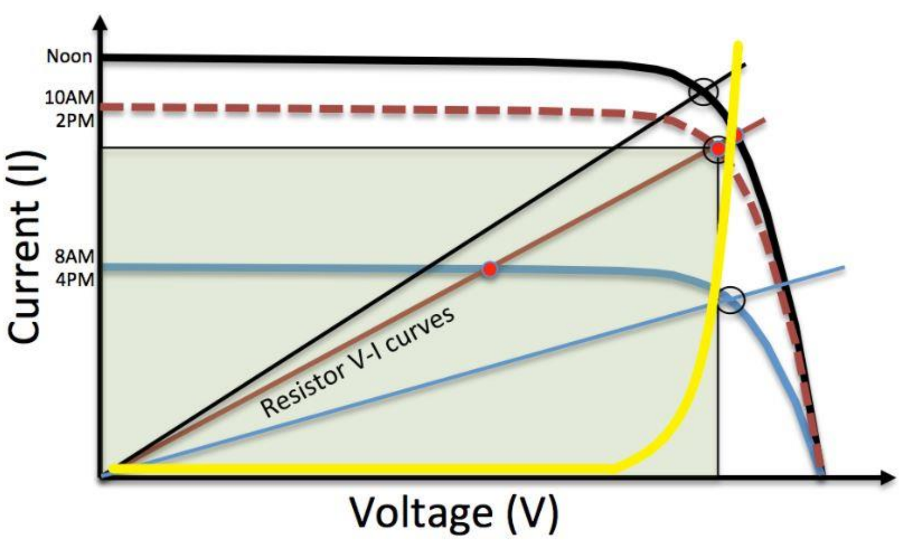


Figure 3. This figure shows the operating characteristics of a photovoltaic cell connected to a diode or resistor. The operating point for the combination lies where the two I-V curves intersect. The power delivered by the system is equal to the current times the voltage at the operating point. As we can see in the figure, the yellow I-V curve for a diode string of proper length is preferable to a resistor as it passes through the operating point corresponding to maximum power regardless of solar intensity (represented by the time of day) [12].

Another beneficial aspect of diodes is that they can regulate voltage. The 1N5408 rectifier diodes each maintain a voltage drop of roughly 0.7 V, so a chain of diodes can be constructed to regulate voltage to charge small electronics such as lights or phones. Diodes are not the most accurate method of voltage regulation, but they are inexpensive, and cost is a driving factor in this design.

Figure 4 shows the circuit diagram for a diode chain that can charge external electronics. The charging terminals are connected across the proper number of diodes to satisfy the charging need of the electronic. For example, most phones require 5 volts to charge, so

$$\frac{5[V]}{0.7\ [V]/_{diode}} = 7.14\ diodes$$

Figure 4 displays the phone charger connected across 7 diodes.

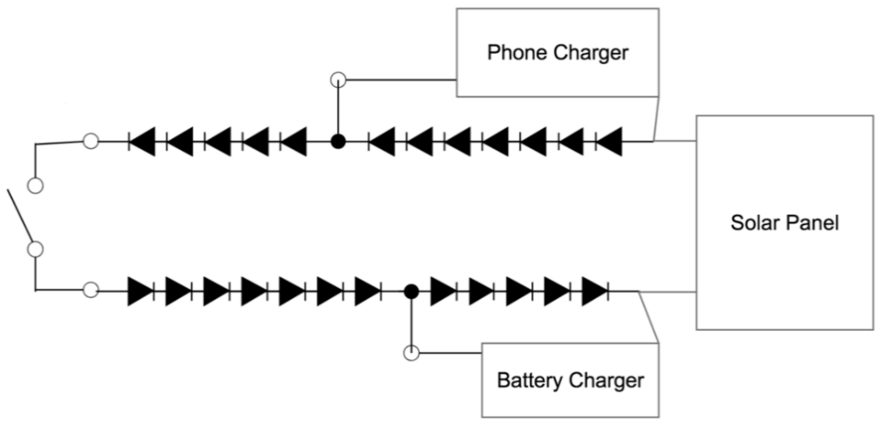


Figure 4. Diode circuit diagram showing configuration to charge other electronics [12].

2.4.2 Thermal Storage

Thermal storage was the main focus of the technical research conducted for this project. Methods of thermal storage depend largely on the operating temperature range of the system. There were two factors that determined this parameter for this device: its purpose and the diodes. As mentioned earlier, Dr. Schwartz' research shows that the diodes themselves cannot exceed 250 °C without failing or becoming damaged but we initially wanted to remain below the manufacturer's recommended operating temperature of 150 °C until testing suggested the design and diodes could support a higher operating temperature. We intended to regulate this through the use of thermoelectric switches that would shut off the diodes if temperatures exceed 150 °C. In terms of the lower bound and its dependency on function, this device is meant to cook food and boil water. As such, this device should comply with federal food safety guidelines which advise heating food to an internal temperature of at least 165 °F, which is about 74°C, during cooking [13]. The cooker should also be able to boil water, which occurs at 100 °C, so boiling sets the lower bound. This initial 100 – 150 °C operating temperature range narrowed the search for thermal storage systems to low temperature systems.

Many thermal storage systems utilize mediums which do not undergo a phase change within their operating temperatures. These types of thermal systems store all their thermal energy in the elevated temperature of the medium which means that in order to store a large amount of thermal energy their medium must reach a very high temperature, or a large amount of medium must be used. This makes such a medium non-ideal for our application, as we need to stay within our range of operating temperature, and we wish to create a device that is both compact and relatively lightweight for thermal efficiency and portability. Thermal storage systems with mediums designed to undergo phase change, however, can store a very large amount of thermal energy in the form of latent heat which allows for greater temperature control with a small amount of medium. Further research confirmed that PCMs were commonly used in thermal storage systems for this very reason and as shown by the previously mentioned "Solar Cooker with PCM Thermal Storage" they have been successfully implemented in very similar products. For the aforementioned reasons, we felt phase change materials were the ideal candidate for thermal storage system within our ISEC.

After selecting the method of thermal storage, the temperature range was used to establish requirements and search criteria for the PCM. For manufacturability purposes, a solid to liquid PCM was desirable. Any PCM that would sublimate or evaporate would need to be carefully contained with relatively complex methods. While these complex sealing methods could possibly be achieved with the resources at Cal Poly SLO, a long-term goal is to have these units manufactured within the communities they serve. It is unlikely that these communities would have these capabilities. Solid to liquid PCMs that would boil within the temperature range must be avoided for the same reasons. A non-boiling, solid to liquid PCM is also favorable from a performance standpoint given that the thermal conductivities of liquids and solids are, on average, orders of magnitude higher than gases.

These preliminary specifications were enough to start the search for a suitable PCM for thermal storage, but the team quickly realized that they were not enough. These criteria alone yielded pure sulfur as a possible option. Further research into sulfur as a PCM showed that sulfur can react with a majority of elements, like those that make up the diodes or pots. These products of reaction can also be toxic which is unacceptable given the PCM's proximity to food. The team altered their PCM requirements after these discoveries. The PCM selected for thermal storage of the ISEC needed to be a non-toxic, non-corrosive, solid to liquid PCM that does not boil in the temperature range of the system.

With these requirements in mind, Dr. Schwartz and Dr. Van Buskirk had previously investigated paraffin wax and various other waxes. There are also several other promising candidates, shown in Table 1, that have been used in similar products. Analysis and testing were required moving forward in order to determine the performance characteristics of interest and select the final PCM for use as the ISEC's thermal storage.

Table 1. Referenced phase change materials that have been used in solar cookers.

Reference	Cooker type	PCM	Tmelt (°C)	Heat of Fusion(kJ/kg)	Cooking medium
Ramadan et al. (2003) [15]	Box	Barium hydroxide octa hydrate	78	–	Water
Sharma et al. (2000) [16]	Box	Acetamide	82	263	Rice and water
Buddhi et al. (2002) [17]	Box	Acetanilide	119	222	Rice and water
Sharma et al. (2004) [5]	Indirect (ETSC)	Erythritol	118	340	Water
Hussein et al. (2008) [17]	Indirect (FPC)	Magnesium nitrate hexahydrate	89	134	Water
El-Sebaii et al. (2009) [16]	Advanced Indoor	Acetanilide	116	142	–
El-Sebaii et al. (2009) [16]	Advanced Indoor	Magnesium chloride hexahydrate	116.7	165–169	–
Nagano et al. (2004) [20]	–	Magnesium nitrate hexahydrate	89	152	–

Table 1 includes a variety of PCMs that are different from paraffin or other waxes and highlights the melting temperatures, which must be inside the range of operational temperatures of our device. Here ETSC stands for evacuated tube solar cooker and FPC stands for flap-plate collector. Cooking medium includes the substances that were heated during the testing of the respective cooker. The cooker tested by Nagano does not have a cooker type or cooking medium because it was used as thermal storage to reduce waste heat from cogeneration systems. The cooker tested by El-Sebaii does not have a cooking medium because it was tested for long term phase change effects without cooking food.

2.5 Ethics: Industry codes, standards, and regulations

It is also of utmost importance that our team designs and produces a safe product. This includes avoiding contamination of food and maintaining external temperatures that will not burn the customer. One of the team's biggest safety and ethical concerns is to ensure that there is no leakage or penetration of the phase change medium into the food that is being cooked. Since the main users/customers are going to be families, they would not want any sort of contamination of the dinner they are serving to their children. Another area of importance for the team is to ensure that the food inside the solar cooker reaches suitable temperatures in order to avoid undercooking and foodborne illnesses. This is highly important since in some developing countries this may not be a requirement of the food cooking products there. Our minimum internal temperature for the food is about 74 °C which meets the required temperature for all foods here in the United States [13].

3 Objectives

This section will highlight the scope of the project and what the team plans on completing. Included are our problem statement, boundary diagram, customer needs, QFD process, engineering specifications, and a discussion of the high-risk specifications that could be difficult to meet.

3.1 Problem Statement

Access to electricity and its accompanying amenities is limited in developing countries throughout the world. Recently, solar electric solutions have been implemented in developing countries in the form of ISECs to reduce dependency on biomass fuels. These ISECs, however, could be improved through the addition of a thermal storage system that would allow for a faster cooking time and provide affordable electricity for powering other small electric devices, increasing overall convenience. This project will develop and implement one of these thermal storage systems to address these issues.

3.2 Boundary Diagram

As shown in the boundary diagram in Figure 5, this project focused solely on the cooking unit itself and the thermal storage system. This area of focus consists of the diode chain, the interior and exterior shells, and the thermal storage medium between the two shells. How power was supplied to the cooker and how the cooker would provide power to other devices, like batteries or lights, had largely been predetermined by the sponsor. Regarding these other electronic functions, this project is only concerned with how to interface with these subsystems and providing the necessary power.

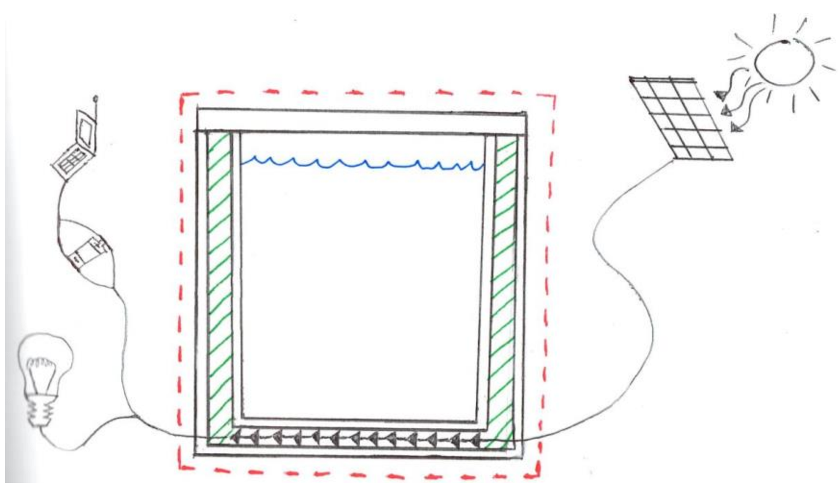


Figure 5. Boundary diagram of the ISEC with phase change thermal storage detailing which specific components of the system are the focus of this project. The team’s focus is limited to inside the dashed lines.

3.3 Customer Wants/Needs

Paramount to this design's success was the necessity for an inexpensive product. The product's users, the citizens of developing countries without contemporary cooking methods, care the most about the total cost. Another important consideration was adding the ability for the solar cooker to charge lights and other small electronics with the surplus electricity. This coupled with the thermal storage ability is critical for developing communities to be able to function past sundown.

3.4 QFD Process

A House of Quality was used to assist the team in finding the suitable areas to focus on based on their relative importance to the project. We started by identifying the customers and requirements of the product and rating the relative weight between each. The team then added engineering specifications for how to complete and measure each product requirement. These relationships are weighed as well, ranging from weak to strong depending on how well the specification measures each requirement. Then, after researching similar products, we rated how well each existing product satisfied each requirement. There are more relationships between each requirement and target values for engineering specifications, but they will not be discussed here. The full QFD house of quality can be viewed in Appendix A. A reoccurring issue that surfaced while filling out the table was the difficulty of finding competitive products that had similar goals or designs. Many similar products were focused on only one, or few, of our design criteria, so implementing aspects from a variety of products would be the best solution to our problem.

3.5 Engineering Specifications Table

In order to organize the engineering requirements for the project, all engineering specifications were tabulated in Table 2. The engineering specifications table includes all product requirements, the target value, risk of the goal not being met, and the method in which the specification is measured.

Table 2. Engineering specifications table. Compliance is verified by Test (T), Analysis (A), Inspection (I), or Similarity to an existing design (S). The potential risk of the design not meeting these specifications is also designated as low (L), medium (M), or high (H).

Spec. #	Description	Target	Risk	Compliance
1	Internal Cooking Volume	2-6 Liters	L	T
2	Internal Pot Temperature	150 °C	M	A, T
3	Complete Charge Time	8 hr.	H	A, T
4	Cook Time from Full Charge	1hr.	H	A, T
5	Total Cost	$30	M	A
6	Mass	14 kg	L	T
7	No Failure Under 400 N Blunt Force	Required	M	T
8	Max. External Temperature	40 °C	L	A, T
9	Liters of Water Boiled in 1 Hour	4 Liters	H	A
10	No PCM Contamination	Zero	M	T

The complete charge time specification means the time for the full amount of PCM to transition from solid state to liquid state. Cook time from full charge represents how long it will take to cook a pot of food when all the PCM is in a liquid state. We selected 400 newtons as the force the cooker must withstand because it is roughly equivalent to the force of a hammer swing. The cooker will most likely be subjected to forces from tipping over or being dropped, so a hammer swing will incorporate a safety factor as well. We also specified no contamination of the food from the PCM as a hard requirement. This is significant because first and foremost, we must create a safe and effective cooker. It is important to note that a subsequent meeting with Dr. Robert Van Buskirk later in the project altered these engineering requirements. These alterations are thoroughly discussed in Section 5.3. These previous requirements have remained in this report as they provided guidance and direction for a large portion of the preliminary design process.

3.6 Measuring Each Specification

All specification testing was done by preliminary design analysis or testing upon completion of the cooker. Since the final product was still a prototype, the team's engineering analysis of the properties was crucial to the project's success.

3.7 High Risk Specifications

The number one priority of the team was to meet the specification of cook time from full charge since that goal was one primary reason this project was being explored. Therefore, meeting the short one-hour timeframe, especially when this cooking is not taking place during the day, was a high-risk engineering specification.

4 Concept Design

This section will cover the selection and specifications of the team's preliminary concept design. The team used many different variations of brainstorming during this time. One method that was used was function decomposition, during which the team decided on a general function (cook food) and subsequently broke that function into multiple subfunctions. Another method was the process known as "SCAMPER". The idea behind this brainstorming method would be to think of aspects of the design using the terms Substituting, Combining, Adjusting, Modifying, Putting to other use, Eliminating, or Reversing a.k.a. "SCAMPER". The team also utilized Pugh matrices that produced system designs with different function combinations for ideation. Finally, a weighted decision matrix was used to evaluate all design concepts and select the best design to move forward with. The chosen design was a simple concentric pot configuration using erythritol as the phase change medium. The cooker included a single diode chain in a hoop configuration around the bottom edge of the inner pot. We will also use fiberglass insulation around the cooker and a 100-watt solar photovoltaic panel as the power source.

4.1 Alternative Design Concepts

In choosing a design to move forward with, we considered function alternatives that may have benefited our device such as pot configuration, diode configuration, phase change material, conduction assistance, insulation, and solar panel power. Some alternative functions included a double PCM pot configuration, using magnesium chloride hexahydrate as the PCM, conduction assistance, using a crown diode configuration, and using a 200 Watt solar panel rather than 100 Watts. The following sections will go over function alternatives for the overall system that we considered but did not choose in our final design.

4.1.1 Double PCM Pot Configuration

The double PCM pot configuration depicted in Figure 6 consists of three concentric pots and two different phase change mediums. This design uses a low melting temperature PCM on the inside and a high melting temperature PCM on the outside. The goal of this configuration was to promote solidification of the outer PCM first and keep the inner PCM in liquid state for a longer time to remedy the solidification of PCM around the cook pot which would insulate the food from the PCM and decrease heat transfer. The double PCM design was not chosen due to the increase in cost and assembly complexity.

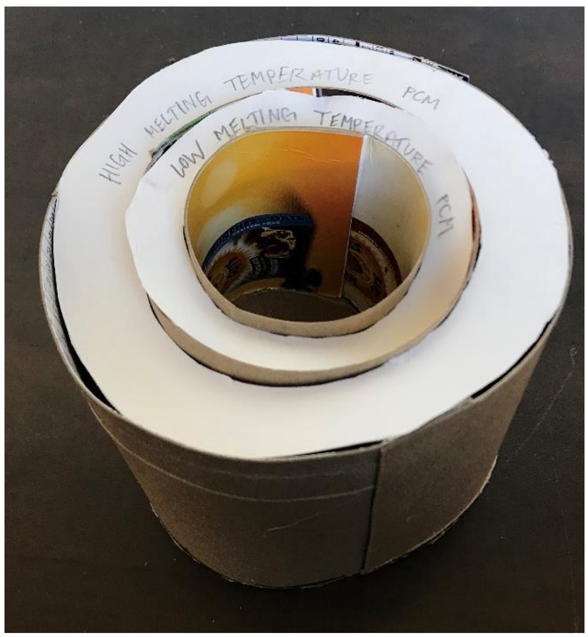


Figure 6. Double PCM Configuration

4.1.2 Diode Crown

Another design concept that was considered was the arrangement of the diodes being in a crown formation as seen in Figure 7. This concept was discontinued due to the unnecessary number of diodes that this would take as well as the unevenness of the shape. After further research, it was determined that a hoop configuration is simpler, cheaper, and accomplishes the same task. Later, when the changes between the first and second prototype are discussed, the improvement in the diode chain configuration is noted.

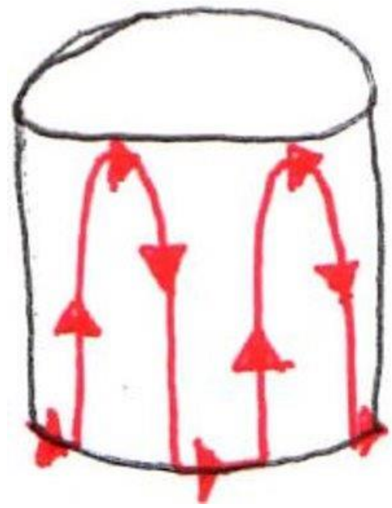


Figure 7. Diode crown configuration

4.1.3 Magnesium Chloride Hexahydrate

One design that was also heavily considered was using magnesium chloride hexahydrate as the phase change material. The team ended up not going in this direction due to magnesium chloride hexahydrate being a salt and having corrosion potential. Another reason that the team decided to move away from this PCM and choose erythritol instead was that magnesium chloride hexahydrate did not have nearly as high a heat of fusion. This comparison is summarized in Appendix B. The team decided to stick with erythritol for the final device.

Figure 8. Magnesium chloride hexahydrate

4.1.4 Conduction Assistance

The team heavily debated on the use fins for added thermal conduction within the PCM, shown in Figure 9. If fins were included, the performance of the device could possibly be improved, but manufacturing complexity and cost would increase. Without fins, the device would be cheaper and easier to assemble, but could fail to melt the PCM. Given the complexity of this engineering tradeoff and the fact that the team planned on constructing at least two prototypes, the team decided that this needed to be a data driven decision and would collect data on a finless initial prototype before revisiting the situation. After results from the initial tests on the first prototype, the team ended up not moving forward with fins.

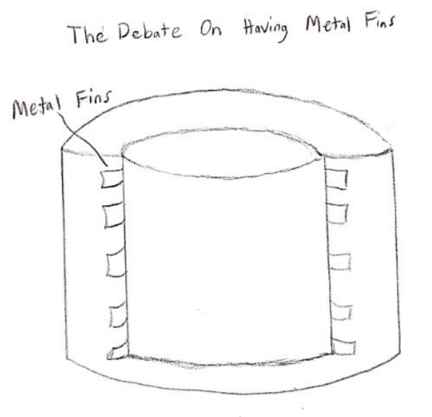


Figure 9. Conduction assistance

4.1.5 Solar Panel Power

The team considered using a 200 Watt solar panel, shown in Figure 9, to power the cooker but did not elect to move forward with the idea based on keeping the cooker cost as low as possible.

200 Watt Panel

100 Watt Panel

Figure 10. 200 Watt PV Panel and 100 Watt PV Panel

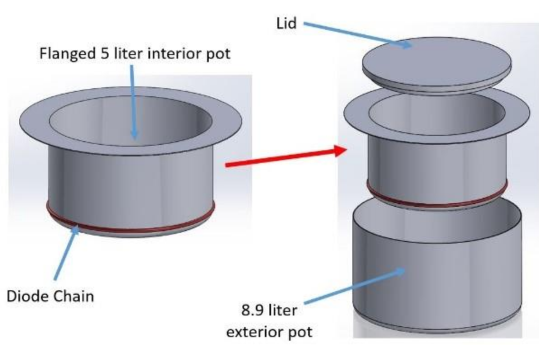
4.2 Concept Design Decision Matrix

To narrow down our design concepts, we used a weighted decision matrix. This decision matrix was used to evaluate different overall system designs. The matrix considered nine potential design concepts, selected from the Pugh matrix frontrunners, and evaluates them based on our selected requirements. The requirements are given a weight that represents the respective importance on the final product. Once each design was evaluated for all design requirements, the design with the highest score was selected as the best design. The full weighted decision matrix, as well as the Pugh matrices for the team's design functions, can be seen in Appendix C.

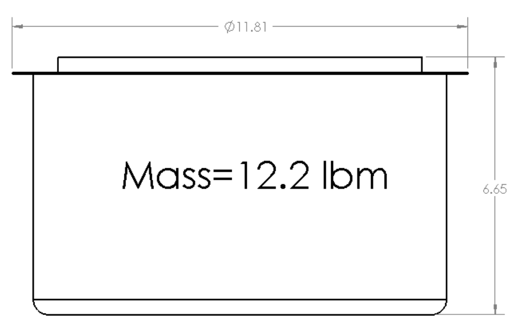
4.3 Selected Concept Design

In order to further define the characteristics of our design, the inner pot dimensions were chosen such that it could hold enough volume to satisfy our design requirements. Then this predetermined inner pot diameter was used with the Engineering Equation Solver (EES) software to determine the outer pot dimension. EES is a powerful tool with a vast library of thermomechanical properties and allows the user to solve simultaneous complex equations. Specifically, this computer program was used to assist us in the exact pot specifications for our first prototype. The full EES codes used to estimate the pot dimensions can be found in Appendix D.

Referring back to our decision matrix, we chose to incorporate the single hoop diode configuration instead of something more complicated for its overall simplicity and its ease of manufacturing. The drawback to the single-hoop diode configuration is that it provides non-uniform heating, but we believe this will not be a significant issue since the diode chain outputs low power over a long-time frame which should give the heat ample time to diffuse throughout the PCM. On our first model, designed to hold erythritol, we chose to not include any additional form of conduction assistance. The models can be seen below in Figure 11.



(a) Isometric SolidWorks model



(b) Mass and dimensions of full ISEC assembly

Figure 11. SolidWorks model of un-finned ISEC, scaled to fit design volume of erythritol.

The cooker and PCM assembly are contained in a larger pot or bucket filled with insulation. The insulation provides thermal resistance on the outside of the pot to reduce the amount of heat lost to the surroundings and keep the external temperature of the cooker low to prevent injury to the user. When selecting the type of insulation, the team compared fiberglass insulation, rice hulls, and perlite in Appendix E and found fiberglass to be the most suitable insulation.

A concept prototype where fins were included was constructed by the team in order to understand how the components might interact with each other during assembly and to gain an overall feel for how the device may look. It is important to note, however, was that this was just done for the concept prototype, and fins were not included in future work. This preliminary concept prototype is shown in Figure 13.

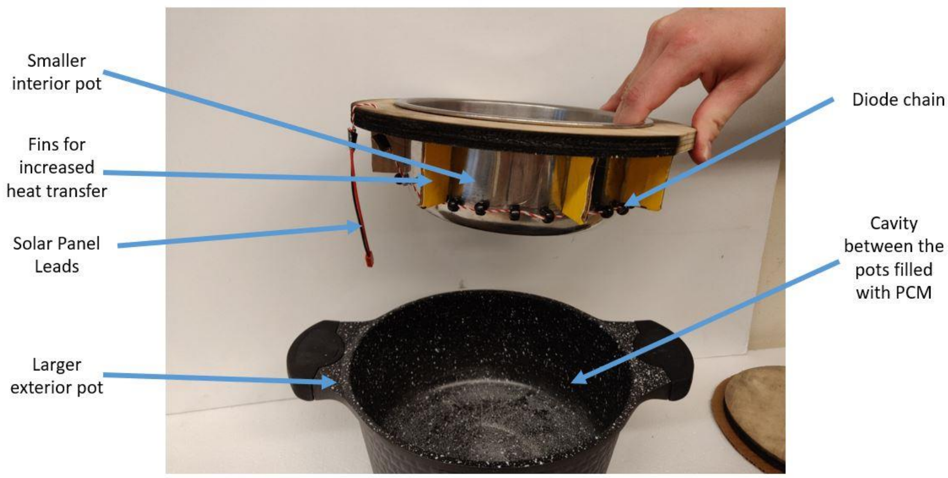


Figure 12. Preliminary concept prototype

4.4 Preliminary Analysis

To justify these design decisions, the team analyzed the temperature distribution throughout the PCM and overall efficiency of the phase change thermal storage through Matlab and EES models. The results of the system models are listed in the following sections.

4.4.1 Finite Difference Conduction Model

Completely melting the solid erythritol was an important requirement of the diode chain. For validation purposes, a two-dimensional nodal network conduction model was used to determine if the PCM surrounding the diodes would reach the 116 °C melting temperature of erythritol. Reasonable surface and diode temperatures were approximated and used to populate the model for an operating point close to the initial powering of the device. Finite difference equations were then used to populate the model in Matlab, shown in Appendix F, and the results are shown in Figure 14. The borders of the figure represent the outer surface of the outer pot while the dark blue silhouette represents the inner pot cavity. Inner pot surface, outer pot surface, and diode temperature were set as 50, 80, and 150 °C respectively.

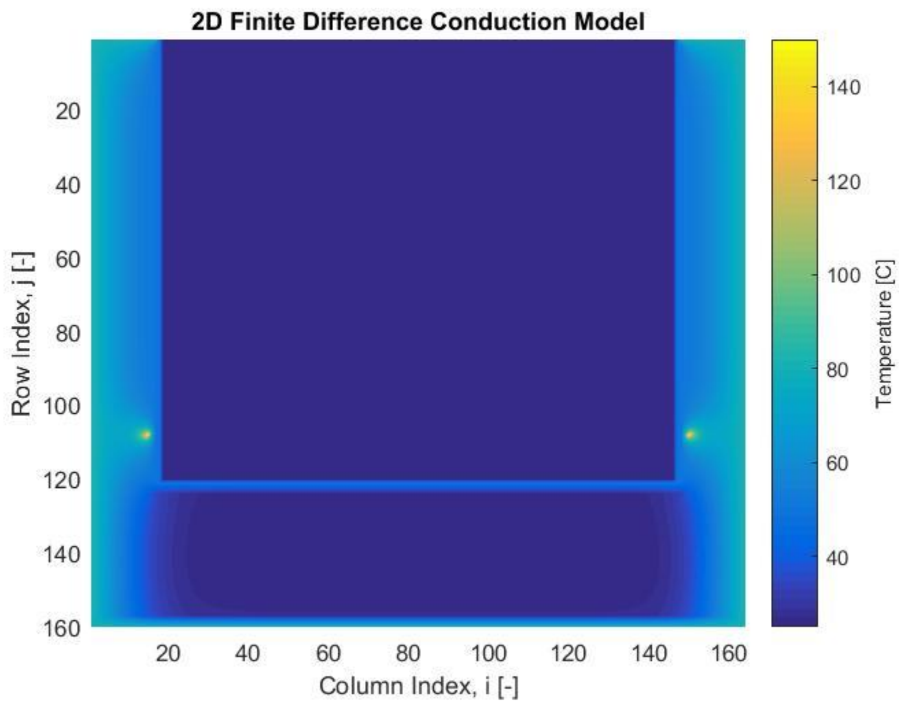


Figure 13. The resulting temperature distribution of the ISEC and erythritol PCM determined by a 2D conduction model and finite difference equations.

As shown by the temperature distribution above, there is small region surrounding the diodes that is predicted to reach the melting temperature. While this result is reassuring, this is still a crude model. This steady state, solid phase model does not consider the transient effects of the PCM melting and the accompanying convection heat transfer. In conclusion, this model suggested to the team that the single hoop diode chain could melt the erythritol.

4.4.2 Lumped Capacitance Thermal Models

With our leading PCM candidates chosen along with our planned solar panel power and desired cooking capacity, we had enough information to perform thermal analysis on our design to determine the required PCM mass using a lumped capacitance model. We calculated this mass using a combination of two metrics. The first metric is the amount of PCM required to meet our minimum energy requirement of bringing 4L of water to a boil from 30°C. The second metric is the amount of PCM which could theoretically be fully melted by our solar panel given a full charge cycle of 8 hours.

Note that both these metrics neglected some inefficiencies in our system which resulted from heat loss, a non-ideal electrical operating point, and inconsistent solar radiation intensity. As a result of these inefficiencies, the first metric will underestimate the amount of PCM needed to boil 4L of water and the second metric will overestimate the amount of PCM our system is capable of melting in a full charge cycle. That being said, the first metric set the lower bound and the second metric set the upper bound for PCM mass. To determine a rough design mass, we took an average of the masses from each metric.

Using this design mass, we were able to calculate the design volume of our PCM cavity. Note, we were sure to incorporate a factor of safety into this design volume such that in its liquid (higher volume) state the PCM would not entirely fill the cavity at the risk of pressure build up and PCM leakage. From the design volume and chosen inner pot dimensions, we were able to calculate the geometry of the outer pot. We chose to maintain a uniform spacing between the outer and inner pot for simplicity.

We coded this lumped capacitance model into Engineering Equation Solver (EES) for both erythritol and magnesium chloride hexahydrate. These full EES codes can be seen in Appendix D. The design mass of erythritol and magnesium chloride hexahydrate were 4.5kg and 6.1kg. The corresponding cost of the erythritol and magnesium chloride hexahydrate would be approximately \$4.51 and \$1.83, respectively, based bulk prices from Alibaba and approximately \$33 and \$43 for small quantities bought for online sellers in America for prototyping.

4.4.3 Derivation of System Efficiency

After talking with our collaborator, Dr. Robert Van Buskirk the founder of the non-profit Kuyere! our project team has decided to slightly alter the scope of our project to better meet the needs of our customers. Robert encouraged our team to focus on creating a smaller capacity ISEC that could be charged over a shorter period with the aim of making the ISEC more convenient and reliable. With a shorter charge time the ISEC would be able to be used for both lunch and dinner if desired on a sunny day and it will still be able to reach full charge and cook one meal on a day with limited sunlight. Dr. Buskirk also stressed that efficiency needed to be one of the primary goals for our ISEC. His logic being that with the solar panel still being the bulk of the ISEC's cost and our end customers having extremely limited economic means, harnessing that solar power as efficiently as possible will be the largest factor in determining the value of our ISEC to our end customer. With this in mind, our team saw it as essential that we fully investigated the different factors that determine the overall efficiency of our system.

First, we defined the efficiency of our system in terms of energy. We can define the efficiency of our system, η_{system}, as the fraction of the energy delivered to the food to the maximum energy the solar panel can collect (which should be roughly the rated power of the panel). Now there are multiple reasons why our system will not have 100% efficiency. Firstly, the panel will not always receive maximum radiation intensity. If there is cloud cover or if the device is operating early in the day or late in the afternoon the intensity will be less than the maximum and the solar panel will not have the ability to generate as much electrical intensity. We can call this efficiency η_{solar}.

After this solar radiation hits the panel wired to the ISEC's diode chain, a voltage will be generated across the diode chain and a current will flow through this diode chain. The diodes will dissipate energy equal to the product of voltage and current as heat. Now, on the solar panel's VI curve there is an operating point corresponding to maximum power. Our actual system will only be able to operate at a fraction of maximum power and this fraction will depend on how well we designed our electrical system (mainly how many diodes we use in our chain). We can define this fraction as $\eta_{electric}$.

Once our ISEC converted the electricity into heat energy, some of that energy went into charging the PCM and some of that energy was lost through the insulation. We defined this fraction of heat energy transferred to the PCM as $\eta_{insulation1}$. Now once the PCM was charged and food was added to the ISEC for cooking, energy stored in the PCM can either be transferred to the food, lost through the insulation, or remain stuck in the PCM. Some energy was stuck in the PCM according to the 2nd law of thermal dynamics which states heat cannot flow from cold to hot. This means that once the PCM hit 100°C, it no longer transferred any energy to the boiling food, and it was effectively lost. We can call the fraction of energy which leaves the PCM over the total thermal energy initially stored in the PCM η_{PCM}. Once the food was added to the ISEC, some of this energy transferred from the PCM went to the food and some was lost through the insulation. The fraction of energy entering the food to the energy leaving the PCM was defined as $\eta_{insulation2}$.

Now multiplying the efficiency of all the steps together we get the total efficiency of our system,

$$\eta_{system}=\eta_{solar}\cdot\eta_{electric}\cdot\eta_{insulation1}\cdot\eta_{PCM}\cdot\eta_{insulation2}$$

So, the overall efficiency of our system was largely dependent on solar intensity, how well we design our diode chain, how conductive our system is compared to our insulation, and what fraction of the energy was stored below 100 °C in our PCM.

Dr. Van Buskirk challenged our project team to produce an ISEC with a system efficiency of over 30%. As will be explained later in the results section, our final prototype was able to accomplish this requirement.

4.4.4 Analysis of Component Efficiencies

Dr. Van Buskirk expressed concern that our system could have difficulty effectively transferring heat while the food is at high temperatures and told our project team that previous ISECs have struggled with the same problem. He was concerned if we would have sufficient cooking power and efficiency with the small temperature difference between our PCM and the food. Exploring this possibility our project team created a MATLAB code to investigate the relationship between our thermal efficiencies ($\eta_{insulation1}$, η_{PCM}, and $\eta_{insulation2}$) and cooking power with PCM temperature. The Complete MATLAB code can be seen in Appendix G.

First PCM efficiency, $\eta_{PCM,}$ was calculated for both erythritol and magnesium chloride hexahydrate at different charge temperatures. These results are shown in Figure 15. Erythritol is much more efficient than magnesium chloride hexahydrate at all temperatures and that both PCMs are more efficient at storing useful energy at higher temperatures. These results are as expected. Erythritol has a much higher heat of fusion and a lower specific heat as a solid, so it makes sense that it stored a larger fraction of its energy above 100°C and increasing the charge temperature added more energy above 100°C. The efficiency for erythritol at 150°C (our planned charged temperature) is 83%. This efficiency is acceptable, it would be very difficult to find another PCM that could match this efficiency. This analysis was very accurate as will be shown later in the results section of this report.

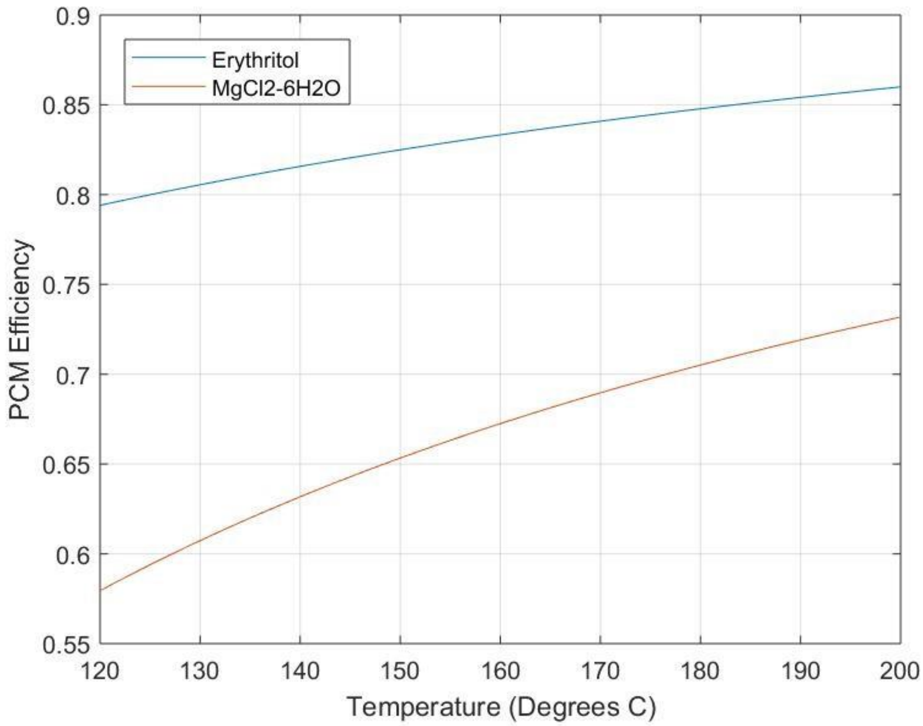


Figure 14. Plot of η_{PCM} versus charge temperature for both erythritol and magnesium chloride hexahydrate.

Second, $\eta_{insulation2}$ was calculated for a food temperature of 100 °C. For this calculation a ratio of the thermal resistance through the insulation versus the thermal insulation to the food needed to be assumed. We assumed a resistance ratio of 20. Depending on how well we insulated our system and how well our system was able to conduct heat to the food, this value could be lower or much higher. Regardless of if this ratio is accurate, the basic trends should be the same.

These r are shown in Figure 16. We marked 3 points of the trend corresponding to different temperatures: one mark is at 110°C, one mark is at 117.5°C, and one mark is at 150°C. The mark at 117.5°C represents the phase change temperature of our current PCM candidates. The mark at 110°C represents the apparent phase change temperature of our current candidates if they exhibit significant subcooling. Finally, the 150°C mark represents a PCM with a significantly higher phase change temperature, such as maltitol [21].

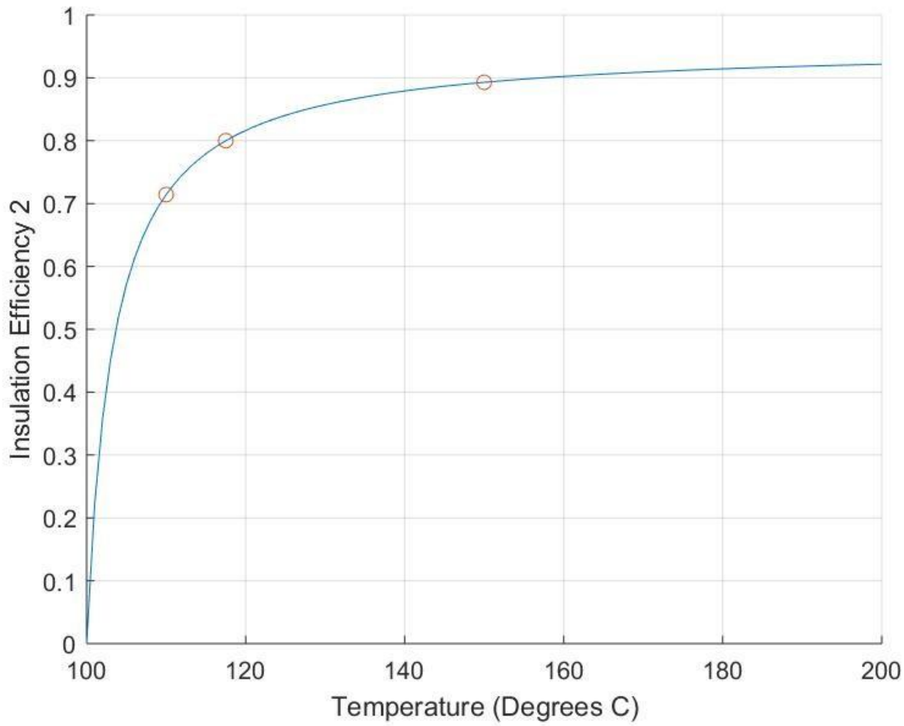


Figure 15. Fraction of energy transferred successfully to food from PCM for different PCM temperatures.

Next, we investigated the energy lost during the PCM charging phase and the cooking power with respect to PCM temperature. Since both the heat transfer to the food and through the insulation from the PCM is dominated by conduction and convection, the heat transfer rate can be modeled as a linear function of temperature. We normalized both of these linear functions such that their value at 117.5°C (the phase change temperature of our current PCM candidates) is 1. The results of this section are shown in Figure 17. From the figure we see that cooking power is much more sensitive to temperature than heat loss. For example, if the PCM temperature is increased to 135°C the cooking power is doubled from the temperature at 117.5°C while the rate of heat loss only increases by 20%.

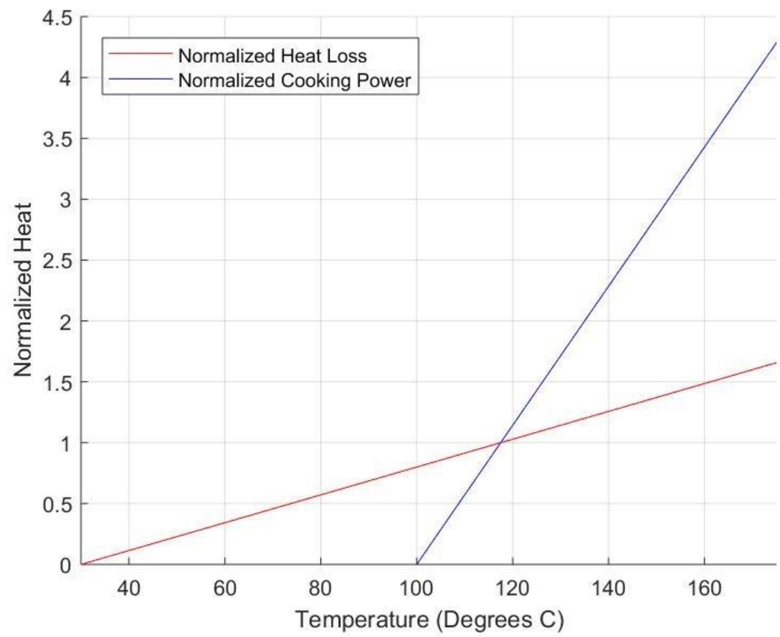


Figure 16. Normalized heat loss and normalize cooking power versus PCM temperature.

The results of Figures 15 and 16 indicate that a PCM with a higher melting temperature would likely be more energy efficient and capable of delivering greater cooking power. The results also indicate that if our current PCMs exhibit significant subcooling that they will be much less efficient and would provide much lower cooking power. Taking all these results into consideration, we still think it is best to move forward in using erythritol for our first prototype. The team did not consider switching from erythritol to a different PCM after the first prototype as is shown later.

4.5 Design Hazard Checklist

The design hazard checklist was used to identify any hazards present in the design and quantify the associated risks. A full checklist is included in Appendix H with the specific risks that apply to our final prototype. Shown by this checklist, the team was careful while using and installing the insulation, as fiberglass can be irritable to skin and eyes. Proper personal protective equipment (PPE) was used while installing the insulation and it was imperative that the cooker was properly assembled with the insulation completely isolated from the food and cooking area. Another hazard the team considered was the overheating of diodes. To resolve any potential problems, a bi-metallic switch was installed in the diode circuit. The bi-metallic switch in series with the diodes creates an open circuit and stops power supplied to the diodes if temperatures reached a prescribed value, 150-200 °C for this application. Then, once the temperature of the diodes decreases to the reset value, the switch disengages and closes the circuit and restores power to the device.

5 First Prototype

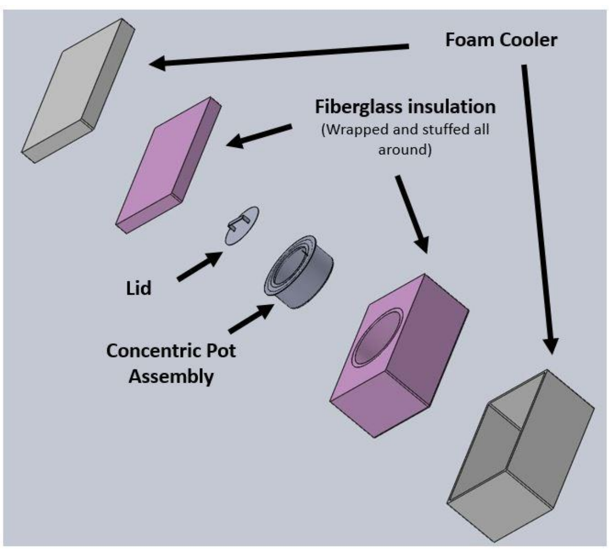
The results from the design hazard checklist along with some preliminary calculations were used to refine the prevailing design from the weighted decision matrix into the following first prototype design. The goal of this first iteration prototype was to prove the basic concept of a using a phase change material as a thermal battery for cooking and to determine any issues with our design so that we could make appropriate design changes on a final prototype. Keeping these goals in mind, our team choose to keep the design simple for the first prototype and to utilize some of the supplies our sponsor already had on hand to minimize the time and monetary costs of the prototype.

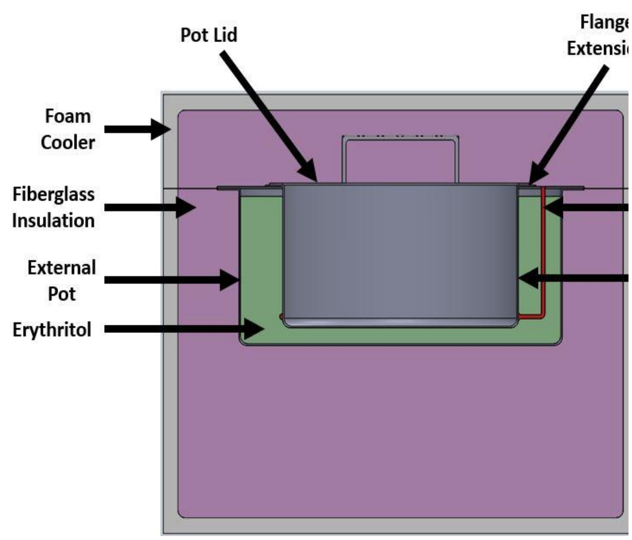
In this section of the report, we will discuss the design, manufacturing, and testing of our initial prototype

5.1 Design Overview

A CAD model of our initial design is pictured in Figure 17. Both an exploded view and a cross-sectional view of our model are shown. Our initial design consisted of a foam cooler, fiberglass insulation, a lid, and the concentric pot subassembly.

The diode chain subassembly and erythritol are contained within the concentric pot subassembly and are shown in the cross-sectional view. These major subsystems and components will be discussed in detail in the following sections.





(a) Exploded View of the Full ISEC Assembly

(b) Cross-Sectional View of the Full ISEC Assembly

Figure 17. The Full ISEC assembly of the first prototype with labeled major components and subassemblies

The ultimate goal of this design is to store thermal energy for the cooker and to increase heat transfer rate to the food for faster cooking. This was accomplished using a phase change thermal storage medium. The cooker is powered by a 100 Watt solar panel connected to the diode chain. The diode chain is submerged in the erythritol and heats the PCM directly. Throughout the day, the diode chain melts the PCM and stores thermal energy, which is kept in the system with insulation. Once ready, the user can put food into the internal pot and the hot PCM will transfer heat to the colder food at a faster rate than the diode chain could provide alone.

5.1.1 Concentric Pot Subassembly

The first major subsystem is the concentric pot subassembly which is shown in Figure 18. This subassembly includes the internal and external pots, the PCM contained between them, the diode chain subassembly, and a flange extension. This subsystem is directly responsible for containing the erythritol and food. These pots are made of aluminum.

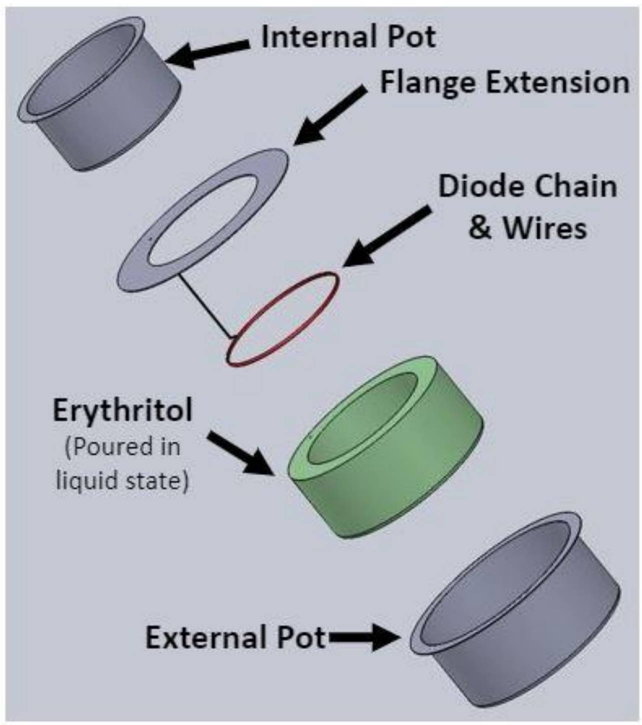


Figure 18. Concentric pot assembly exploded view with labeled components

5.1.2 Flange Extension

The flange extension in the concentric pot subassembly, shown in Figure 19 was the most complex component of our design from a manufacturing standpoint. This flange extension, made from sheet metal, separates and lifts the internal pot away from the external pot while covering the erythritol filled cavity between them as shown in Figure 18. The inner diameter of the flange extension had to be larger than the outer diameter of the internal pot walls but could not exceed the outer diameter of the internal pot flange. Meanwhile, the outer diameter of the flange extension needed to be larger than the inner diameter of the external pot walls in order to bridge the gap between the two concentric pots. Holes for the diode chain leads and thermocouples also needed to be cut into the flange extension above the PCM cavity so that power could be supplied to the heating element and the temperature of the PCM could be monitored.

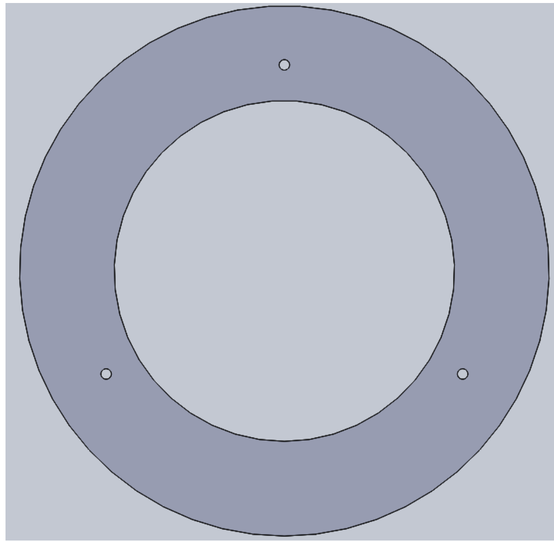
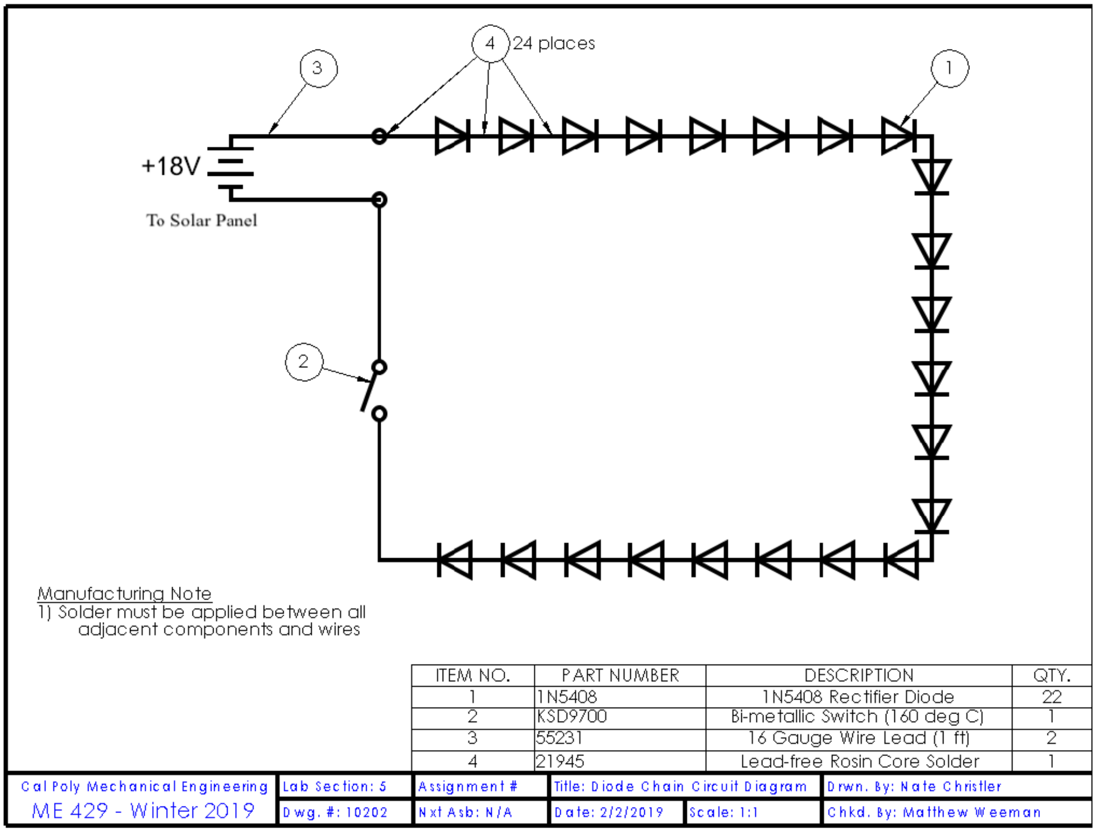


Figure 19. Flange Extension between the Internal and External Pot

There are several methods for cutting straight line geometry in sheet metal but the methods for cutting precise curves into sheet metal, like the concentric circles that needed to be cut into this flange extension, are more restrictive. These curve cutting techniques are further limited by the fact that we wanted a continuous, solid ring. This means the inner circle cut could not start from the outer circle. For these reasons, the team elected to use a water jet cutter to manufacture this component. We recognize that water jet cutters are not the most accessible technology, especially in the developing communities we ultimately wish to help. This is an instance where our proof of concept project goal allows us to deviate from designing for the end customer. Ultimately, the flange extension should be eliminated through an iterative design approach. In order to begin that iterative process, the concept of phase change materials as a thermal storage system must be proven as something worth iterating. The earlier the team can validate this concept, the earlier the process of redesigning our project for the end user can begin. As a result, we believe that utilizing the water jet cutter helped accomplish this goal.

5.1.3 Diode Chain Subassembly

The second major subsystem is the diode chain. This subsystem is the heating element of our cooker and is responsible for utilizing the power from the solar panel to melt the erythritol and ultimately cook the food. As a result, the diode chain is the most critical subsystem of our design. The diode chain was constructed using 22 diodes, a bi-metallic switch, and wire leads. A 100 Watt photovoltaic panel provides power to the diode chain which in turn provides heat to the PCM. The bi-metallic switch was submerged in the PCM and will open the circuit if the temperature exceeds 150 °C. The circuit diagram for the diode chain can be seen in Figure 20 and a completed diode chain is also shown in Figure 21.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1N5408	1N5408 Rectifier Diode	22
2	KSD9700	Bi-metallic Switch (160 deg C)	1
3	55231	16 Gauge Wire Lead (1 ft)	2
4	21945	Lead-free Rosin Core Solder	1

Figure 20. Circuit diagram drawing of the ISEC with thermal storage prototype 1 diode chain

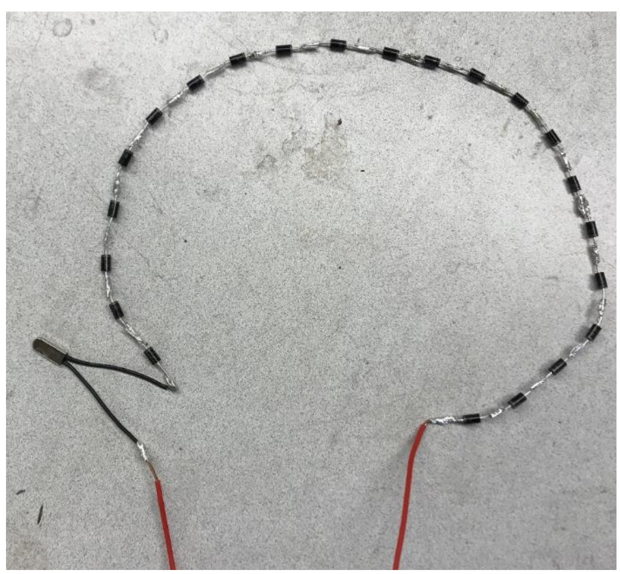


Figure 21. Completed diode chain with 22 diodes, bi-metallic switch, and wire leads.

5.1.4 Housing and Insulation

The remaining major components of this design are the housing and insulation. This includes the foam cooler, fiberglass insulation, and pot lid. The pot lid is placed on top of the concentric pot subassembly to seal the cooking pot. The concentric pot subassembly with lid is designed to be placed in the center of the foam cooler with fiberglass insulation stuffed all around.

5.2 Design Justification

When originally creating the design for the first prototype of the ISEC, the team kept all required design specifications in mind. As we briefly discussed in section 4.4.3 of the report, after talking with our collaborator Dr. Robert Van Buskirk, our team determined it was necessary to change the design specifications of our ISEC from what we initially specified in our scope of work. In addition, after performing some preliminary calculations and analysis, our team was able to better define what our ISEC could be capable of and what our team will be able to accomplish during our project. Taking these changes into account our team felt it was necessary to redefine our project's design specifications. These updated specifications can be seen in Table 3.

Table 3. Updated engineering specifications table. Compliance is verified by Test (T), Analysis (A), Inspection (I), or Similarity to an existing design (S). The potential risk of the design not meeting these specifications is also designated as low (L), medium (M), or high (H).

	Spec. #	**Description**	**Target**	**Risk**	**Compliance**
Critical Specifications	1	Energy Efficiency	30%	M	T
	2	Charge Time	2-4 hr	M	T
	3	Volume of Water Capable of Being Brought to Boil	1.5 L	H	T
	4	Time to Boil 1L of Water	20 min	H	T
	5	Manufacturing Cost	$30	M	A, S
Non-Critical Specifications	6	Concentric Pot Mass	< 14 kg	L	I
	7	Internal Cooking Volume	1.5 L-3.0 L	L	I
	8	No Failure Under 400 N Blunt Force	Required	L	S
	8	Max. External Temperature	40 °C	L	T
	10	No PCM Contamination	Zero	M	I
	11	No Food Contamination	Zero	H	I

This updated specification table is broken down into critical specifications and non-critical specifications. Specifications that our team has deemed critical are specifications that must be met for our ISEC to be successful. Specifications which our team has deemed non-critical on the other hand, are specifications which our team would like to meet with our ISEC but are not the main focus of our project. Failing to meet a non-critical specification will not make our ISEC an overall failure. As stated before, the overall goal of our project is to create a working proof of concept prototype for an ISEC with a thermal storage medium. Our team believes only the critical specifications are essential to prove this concept. That is not to say that non-critical specifications are unimportant to the design of an ISEC with thermal storage. Before such an ISEC is to be implemented all these smaller issues will have be worked out but we believe that as long as the critical specifications are met, the smaller issues can easily be fixed further down the line in a sequential ISEC project.

Efficiency – This specification is critical because one aspect of this design is to compare its cooking ability to that of a battery powered device. This specific cooking method not only needs to work but must be competitive to other methods in order to be appealing.

Complete Charge Time – Robert Van Buskirk, who has deployed solar lighting and previous ISEC cookers in the communities we intend to serve, believes the citizens will prefer if they can use the cooker twice in a day. This information re-shaped the scope of the project to now make a faster, more compact cooker.

Boil Time from Full Charge – Cook time is critical simply because it must be low for the cooker to be useful. PCM thermal storage is supposed to increase the heat transfer to the food in addition to storing energy.

Total Cost – Cost is of utmost importance because for the cooker to be useful, low income communities must want to buy it. As stated previously in section 5.6, the estimated cost of the cooker produced in bulk is under $30.

No PCM Contamination – The team wants to avoid any contamination, but this specification has been deemed non-critical because the cooker can still operate
The flange extension that separates the external and internal pots is connected with JB weld and prevents any significant outside particles from entering the PCM chamber.

No Food Contamination – This is under the non-critical specification category because it is not necessary for the cooker to be tested. Regardless, the team will still test the cooker with water to obtain data for the cooker energy storage aspect.

No Failure Under a 400 N Blunt Force – The team has not tested this requirement yet but is confident that it can be easily met. From outside research, the punching force required to pierce through 0.05-inch-thick aluminum sheet metal exceeds 1500 N.

Max External Temperature – The team also feels confident this requirement can be easily met from the efficiency calculations. The actual insulation thickness will be much greater than the required amount to reach the desired efficiency.

Our team feels confident that our current design can meet the critical specifications and the majority of the non-critical specifications. In the following sections, we will address all design specifications and discuss the reasoning behind why we believe our design will or will not be able to meet the specifications.

5.2.1 Efficiency

In order for our ISEC to be a viable cooking device, it must be energy efficient to provide enough heat while remaining low cost. Dr. Robert Van Buskirk, our collaborator who is implementing these ISECs within Africa, told us to aim for a minimum of 30% overall system efficiency. As discussed previously in Section 4.4.3 of our report the overall energy efficiency of our system is comprised of several constitutive pieces represented in the following equation,

$$\eta_{system}=\eta_{solar}\cdot\eta_{electric}\cdot\eta_{insulation1}\cdot\eta_{PCM}\cdot\eta_{insulation2}$$

$\eta_{insulation1}$ represents the fraction of the thermal energy that is stored in the PCM while charging and $\eta_{insulation2}$ represents the fraction of transferable energy stored within the PCM that is transferred to the food. Both insulation efficiencies account for the energy lost from dissipated heat which is largely dependent on the thermal resistance of our insulation. To get a rough estimate on how much heat would be lost through our insulation, we utilized a simple one-dimensional conduction model. But our ISEC is a much more complex thermal system with three-dimensional geometry and multiple forms of heat transfer that would require additional analysis. Currently, this preliminary calculation is good enough as an estimation.

To calculate the thermal resistance of our insulation, we only considered the resistance of the fiberglass and not the foam cooler or other minor thermal resistances. Since the insulation thickness varies greatly, we used the minimum thickness of the fiberglass insulation, 1.15 inches, as our insulation thickness. We used the total outside area of our exterior pot for the cross-sectional area of insulation. All of these assumptions are quite conservative and over predict heat loss. To determine the temperature gradient across the insulation we used the difference between the average internal pot temperature over a full cycle and the ambient air temperature (30°C). To determine the average internal temperature of the cooker, we simulated a full charging and discharging cycle. For this simulated cycle we assumed that while charging, the PCM was absorbing energy at a rate of 85 Watts and while discharging, the PCM was losing energy at a rate of 300 Watts. In this cycle, the temperature of the PCM was calculated from its stored thermal energy using a lumped capacitance model at every second. The plot of cooker temperature vs time for this cycle can be seen in Figure 22, and demonstrates the average temperature over the entire cycle is 113°C.

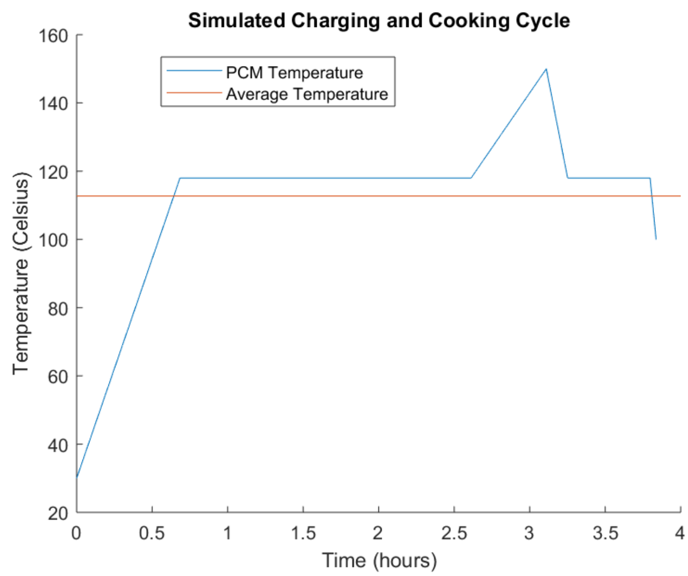


Figure 22. Simulated charging and cooking cycle for erythritol.

A diagram of the complete thermal circuit can be seen in Figure 23. The heat loss predicted by the circuit was 27 Watts which corresponds to an efficiency of 73%. The team defines this efficiency as $\eta_{insulation}$, as it accounts for both the major components of the previously defined $\eta_{insulation1}$ and $\eta_{insulation2}$. All calculations leading up to this thermal circuit were done using a MATLAB code which has been attached in Appendix I for reference.

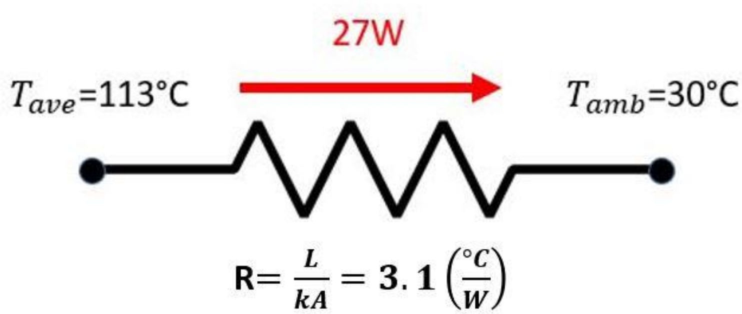


Figure 23**.** 1-D thermal circuit representative of our insulation.

Now that we had an estimated value for $\eta_{insulation}$ and remembering that we already calculated the value of η_{PCM} to be 83% for erythritol at a maximum temperature of 150°C, we had two of the largest sources of inefficiency accounted for. We can rewrite the equation for total system thermal efficiency as follows,

$$\eta_{system}=\eta_{insulation}\cdot\eta_{PCM}\cdot\eta_{other}$$

In this equation η_{other} accounts for all other sources of inefficiency. These sources of inefficiency come from non-ideal solar conditions, non-optimal diode chain length, electrical losses, and heat energy lost when the cooker is open (e.g. when food is being added). These losses are more difficult to quantify. Solar losses should be small as we are designing our device to be used in countries which receive a lot of sunlight. From previous ISEC groups we know that electrical losses can be quite small when proper diode chain length is used. Heat energy lost when the cooker is open could be significant, but if the cooker is not left open and uninsulated for long, heat loss can be minimized as well. Taking all these factors into consideration, as long as η_{other} is greater than 66%, which we predict is highly likely for these smaller losses, our ISEC should have an overall efficiency of at least 40% which is quite a bit higher than our minimum requirement of 30%.

5.2.2 Charge Time and Cooking Capacity

Using the efficiencies calculated in the previous section, we could calculate how much PCM we should use within our design and the amount of water we could expect to boil for a chosen charge time using a lumped capacitance model. We used EES to analyze this lumped capacitance model. The code can be seen in Appendix J. Since our design specification for charge time is to fall within the range of 2-4 hours, we chose 3 hours for the design charge time. Now if we assume that solar and electrical inefficiencies are as low as we expected, the charging efficiency of the device, which shall be defined as the percentage of the nominal 100 Watts that is delivered to the PCM while charging, can be estimated as the insulation efficiency. There will of course be some electrical and solar inefficiency, but since we almost certainly under predicted the efficiency of our insulation this should be a fair estimate. Using our lumped capacitance model, we predicted our device should be able to fully charge 1.5 kg of erythritol in 3 hours.

Now, instead of using 1.5 kg as the design mass of PCM, the team chose to use 1.7 kg. Our reasoning behind using slightly more mass than our calculations predict is that it is better to "undercharge" than to "overcharge" our device. Undercharged for our device simply means the PCM is not heated all the way up to 150 °C. While this will slightly lower the PCM efficiency of our device, as can be seen in Figure 15, the net effect to the overall efficiency will be minor. On the other hand, when the ISEC is overcharged, all the energy put in past full charge must be diverted and therefore lost. The reasoning behind diverting this energy is to prevent our device from overheating and potentially becoming damaged. This waste of potentially useful energy makes overcharging less efficient. Therefore, we chose to design the ISEC with more PCM to err on the side of undercharging.

Using our estimated minimum overall efficiency of 40% and the 3-hour charge time, our lumped capacitance model predicted we would be able to bring 1.5 kg of water to boil from ambient conditions, which meets our design specification. If our device could attain a higher overall efficiency, more water could be boiled.

5.2.3 Cooking Speed

One of the main reasons we are adding a thermal storage medium is in hopes of amplifying the cooking power of the ISEC and improving cooking speed. In order to meet our goal of bringing 1 L of water to a boil in 20 minutes we would need 243 Watts of power as calculated below:

$$P = \frac{mc\Delta T}{t} = \frac{(1kg)\left[4180\left(\frac{J}{kg \cdot ℃}\right)\right](100℃ - 30℃)}{1200s} = 243W$$

This is over 3 times the net power output of the original ISEC. The rate of heat transfer is dependent on the thermal resistance and the temperature gradient. Unfortunately, our ISEC is quite a complex thermal system and we cannot accurately predict the overall heat transfer coefficient. That being said, we can predict a very rough range of heat transfer coefficients through comparison.

For our lower bound we can treat our system as if there is only conduction heat transfer. This will greatly underpredict the heat transfer rate as erythritol has a very low thermal conductivity. For our upper bound, we can use the free convection coefficient of motor oil. Our team believes motor oil is an appropriate fluid for comparison as it is both very viscous and, like erythritol, has a very low thermal conductivity. On a reference website we found that motor oils have convection coefficients ranging from 50-350 $\left(\frac{W}{m^2K}\right)$ [22]. For a conservative estimate we could say our erythritol has a convection coefficient of only 100 $\left(\frac{W}{m^2K}\right)$. If we only take into consideration the thermal resistance of the erythritol (which is fair because we know the thermal resistance of the very thin aluminum pots and the free convection of the water being boiled should both be low), the thermal resistance could be as high as 1.1 $\left(\frac{K}{W}\right)$ or as low as 0.22 $\left(\frac{K}{W}\right)$.

Using these resistance values and a lumped capacitance model to calculate the temperature gradient at each timestep, the time to boil 1 liter of water was calculated in a second portion of the MATLAB code shown in Appendix I. The code estimated that the time to boil could be as low as 11.5 minutes or as high as 55 minutes. This is an extremely rough calculation but our specification (20 minutes) does fall within the estimated range which suggests that as long as convection plays a significant role of heat transfer inside our PCM, we have the potential to meet our specification.

5.2.4 Non-Critical Specifications

We should be able to meet most of our non-critical specifications with relative ease. The concentric pot mass, which we chose to limit to 14 kg for portability, should pose no issue. As previously mentioned, we only plan on using 1.7 kg of PCM within our ISEC and the pots are made from thin and lightweight aluminum. Our device mass will likely be between 2.5 kg-5 kg. We should have no issue finding an interior pot with a volume within the range of 1.5 to 3 liters as most cook pots are around this size. Our pots should be able to withstand a 400 N blunt force without shearing easily. We found that to punch a 1/8-inch diameter hole through aluminum sheet metal as thick as our pots, over 1500 N of force would be required [23]. This should make our ISEC more than durable enough for the expected use. The max external temperature specification was meant to prevent the possibility of injury from burns resulting from contact with the device housing as well as prevent the possibility of starting a fire. Based on the copious amount of insulation we have surrounding our cookpots we should have no issue meeting this requirement.

Not contaminating the PCM or the food might prove to be more difficult specifications to meet. In our design, our team plans to use fiberglass as our primary insulation which could potentially shed particles into the cook pot or PCM cavity. We are less concerned with the contamination of the PCM as we only plan to add a few small vent holes to our PCM cavity which will limit contamination. In addition, the PCM should still function even with foreign particles mixed in. Contamination of the food is a larger concern, if fiberglass particles were to shed into the cooking pot, this could be a health hazard and cause injury to the user. Now, since our device is only meant to show proof of concept, no one will be eating any food cooked with the ISEC. If our ISEC successfully meets the critical design specifications, it would be fairly easy to adapt our design to utilize one of the many food-safe insulating materials or to modify the lid system to prevent potential contamination.

5.3 Preliminary Testing

The team completed some preliminary testing to assist in verifying the design and estimating the performance of the ISEC cooker. All testing took place in room 109 of the Bonderson Project Center on the Cal Poly SLO campus.

5.3.1 Melt Test

The team constructed a truncated chain of 5 diodes to test the melting ability of the diodes and melting properties of the erythritol. Due to the decrease in number of diodes, the supplied voltage had to be decreased as well. The experimental setup for the erythritol melt test can be seen in Figure 24.

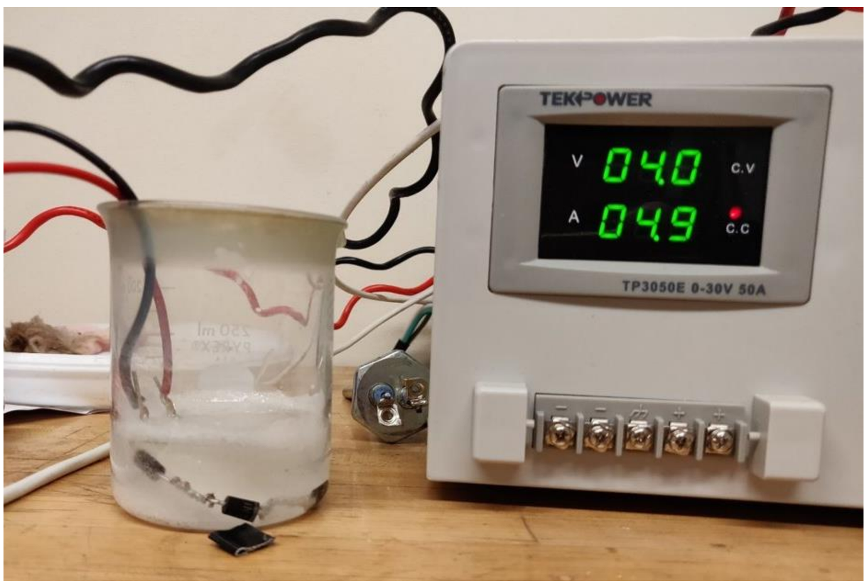


Figure 24. Erythritol melt test setup

The test was completed over a 2-hour period. The beaker test used a significantly reduced amount of erythritol, so the power density of the test was more than double the full-scale power density. At the end of the test, the maximum erythritol temperature was 126 °C and localized melting of the erythritol around the diodes was achieved as shown in Figure 25, but the erythritol further away from the diodes remained solid. We believe we were unable to get greater melting in this test primarily due to lack of insulation. Promisingly, the diode chain performed as expected and no electrical issues occurred. Also, the erythritol showed thermal stability and behaved as expected.

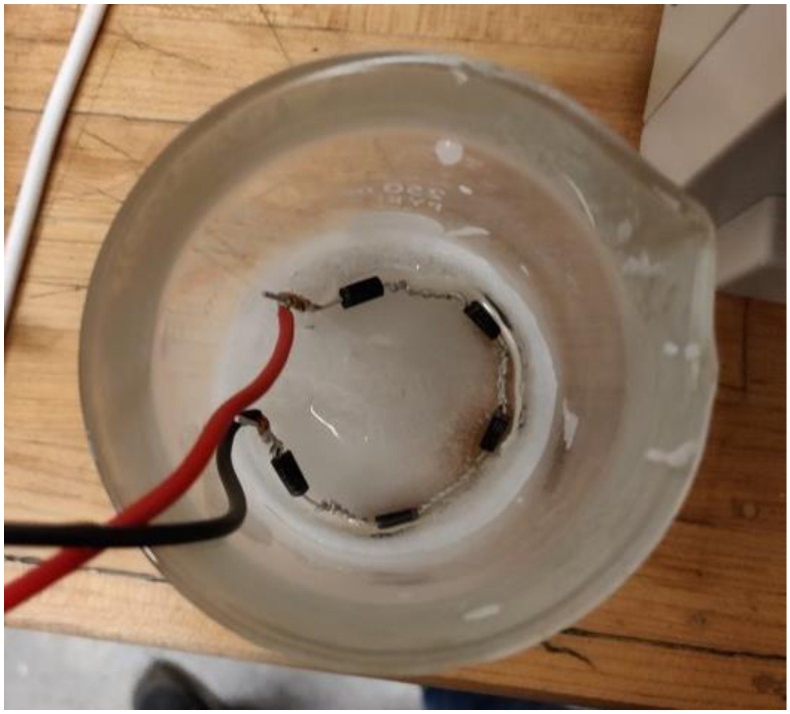


Figure 25. Top view of partially melted erythritol

5.3.2 Current Test

In addition to the melt test, the team tested the full-scale diode chain for proper operation. In this test, voltage was applied across the diode chain and gradually increased while current was monitored. The experimental setup for the diode chain current test can be seen in Figure 26.

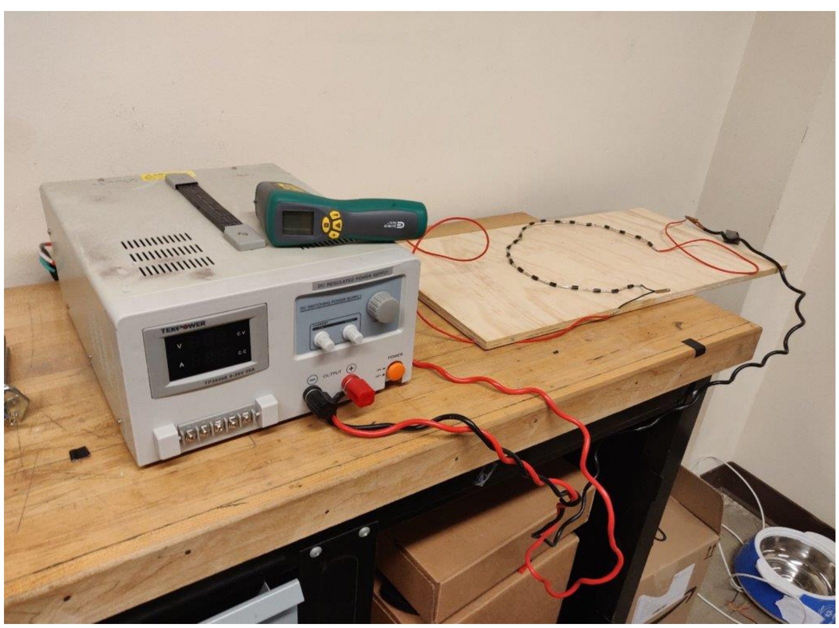


Figure 26. Current test setup

During the test the diode chain failed when the voltage across was increased to 14 V, well below the operating voltage of 18 V. The failure occurred in the solder between two of the diodes. The point of failure can be seen in Figure 27.

Figure 27. Diode chain solder failure when in straight lead configuration

Comparing the full diode chain current test to the beaker test the length of the diode chain used, the surrounding medium, and the method of joining the diodes were different. In the beaker test the diodes were submerged in erythritol, a more effective medium for conducting heat away from the diode chain than air. In the beaker test, the diode chain used was also joined via twisting and soldering which provides a sturdier physical and electrical connection between diodes than solder alone that was used in the current test. Taking this into consideration, the team decided it was best to twist and solder the diode chain in the future to decrease risk of electrical failure.

5.4 Safety, Maintenance, and Repair

Many safety considerations were bought up during our design process, specifically maintaining the ISEC's ability to remain food safe, preventing fires due to exposed wires, and potential leakage of hot PCM from the cooker. Preventing these from occurring through proper manufacturing and proper sealing of the two concentric pots was the team's highest priority from a safety standpoint. Due to our design being a solar electric cooker, there is not much inherent maintenance other than cleaning the pots or the solar panel. Our key focus was more on the issue of repairing the device if a component fails and the system becomes inoperable. When considering how to repair this apparatus, we decided that the most logical approach is to remove the JB weld along the flange extension to gain access to the PCM chamber and diode chain. At this point, any necessary restoration can be completed with the two pots separated. Upon completion of repair, the two pots will be resealed using JB weld.

Our biggest component and process concerns can be found in our FMEA and Design Hazard checklist in Appendix K and Appendix H, respectively. The biggest area of importance to the team was preventing the solder from melting and causing an electrical failure in the diode chain. This can be seen in our risk priority number (RPN) with a rating of 175. An RPN is a relative rating comparing the risk of different failure modes within our design against other failure modes. The electrical failure due to solder melting RPN is much higher than the next biggest risk of PCM failure which was given an RPN rating of 72. These RPN ratings were given by considering the severity of failure, the probability of occurrence, and the detection ability of each failure. Each of these aspects were rated on a scale from 1 to 10 and subsequently, all three columns were multiplied, giving an RPN for the failure mode. As stated previously in 5.4.2, the current test showed the diode chain solder to be the main repair issue of the team moving forward.

5.5 Cost Analysis

One design requirement the team set earlier was to produce the cooker, excluding purchase of the solar panel, for less than $30. Table 4 includes the cost of the cooker with and without the solar panel because although the panel is critical to the function of the cooker, altering the solar panel is outside the scope of the project. Different price points are also included because all items necessary to build the ISEC with thermal storage cooker can be purchased in bulk at discounted rates and the team is re-using materials that Dr. Schwartz already had to build the prototype cooker. Components in Table 4 with an "N/A" value were purchased previously and did not need to be bought for the team. Values for cost at scale were estimated from research done by the team as well as information from Dr. Peter Schwartz and Dr. Van Buskirk. The team estimated all material costs to build the ISEC with thermal storage cooker in bulk to be $28.50. The full indented bill of materials can be viewed in Appendix L and the supplier list representing cost at scale is included as Appendix M.

Table 4. Cost analysis summarizing cooker cost for different customers.

Item	Cost	Cost to us	Estimated Cost at scale
Exterior and Interior Pots	10.00	N/A	8.00
Erythritol	17.25	17.25	6.00
JB Weld	23.04	23.04	4.00
Diode Chain	5.60	N/A	2.00
Aluminum Sheet Metal	13.94	13.94	N/A
Fiberglass Insulation	15.00	N/A	2.50
Foam Cooler Lid and Base	20.00	N/A	6.00
Subtotal	**104.83**	**54.23**	**28.50**
Solar Panel	80.00	N/A	60.00
Total Cost	**184.83**	**54.23**	**88.50**

5.6 Required Manufacturing - First Prototype

The first prototype ISEC with thermal storage only required extra manufacturing for two components: the diode chain and flange extension. All other items are used for assembly only and require no further alterations. Detailed drawings of all critical assemblies and manufactured components can be found in Appendix N.

5.6.1 Diode Chain - First Prototype

Creating the diode chain requires 22 1N5408 rectifier diodes, a bi-metallic switch with 150 °C cut-off temperature, two 1-ft wire leads (stripped ends), lead free rosin core solder, and a soldering iron. First, all 22 diodes must be connected in series, with note to keep diode polarity constant throughout. The spacing between the centers of adjacent diodes should be approximately 3 cm apart. To join the diodes, the leads should be twisted together to ensure physical contact and proper strength and then soldered together. Once the diodes are connected, the bi-metallic switch is soldered to the negative (ground) side of the chain. Finally, 1 ft of wire leads must be connected to each side: the positive end of the diode chain and the remaining wire of the bi-metallic switch. Note that the bi-metallic switch will function regardless of wire polarity. This diode chain was assembled in the Bonderson Project Center on campus.

5.6.2 Flange Extension - First Prototype

The flange extension was cut out of a 1 ft by 1 ft piece of 14-gauge aluminum sheet metal (0.063in thickness). The team used a water jet cutter in the Industrial Technology and Packaging shop on campus to cut out the metal ring, but other acceptable options include a plasma cuter, properly sized circular hole saws, or an adjustable circular sheet metal hole cutter. After the flange extension was cut, three holes were drilled into it 120 degrees apart from one another using a hand drill to allow access for the diode chain wire leads and thermocouples.

5.7 Assembly Order of Operations - First Prototype

1. Clean pots to bare metal

   Note: For the first functional prototype, the team re-used pots and had to clean JB Weld off the exterior of the pots.

2. Construct diode chain

   Refer to section 5.6.1 for diode chain manufacturing details.

3. Cut flange extension and drill holes

   Refer to section 5.6.2 for flange extension manufacturing details.

4. JB weld flange extension and diode chain to interior pot

   First, place JB weld on the bottom side of the pot flange. The flange extension is then placed around the inner pot and slid up to the pot flange to make contact with the JB weld. Next, JB weld the diode chain around the bottom fillet of the inner pot using JB Weld high temperature putty. Care must be taken to avoid touching the diode leads to the pot and shorting the circuit. Let the JB weld set overnight. The attached flange extension and diode chain can be seen in Figure 28.

(a) Full diode chain attached to the pot fillet with flange extension attached to inner pot flange

(b) Close-up of diodes embedded in the JB weld putty

Figure 28. Diode chain JB welded to the internal pot

5. Run diode chain leads and thermocouples through holes

Pull the diode chain wires and thermocouples up from the bottom of the pot through the holes in the flange extension.

6. Measure out 1.8 kg of erythritol and melt erythritol

The team used an oven to melt the erythritol, as seen in Figure 29. Any method of heating the erythritol past 118 °C to melt is acceptable.

Figure 29. Melting erythritol in the oven

7. Prepare external pot for assembly

The external pot must be clean before assembly to avoid any contamination of the PCM. Then, when the erythritol is melted and ready to pour, place JB weld on top of the external pot flange at 3 locations around the diameter. An example of JB weld placement can be seen in Figure 30.

Figure 30. Applying JB weld to the top of the exterior pot flange

8. Pour erythritol into exterior pot and secure interior pot into position

Once melted, the erythritol is poured into the outer pot and the inner pot is placed in the outer pot. To compress the flange extension onto the exterior pot while the JB weld set, the team placed a weight in the interior pot and left it overnight. The pouring process and pot assembly is depicted in Figure 31.

(a) Pouring molten erythritol into the exterior pot

(b) Securing the interior pot in position for JB weld to set

Figure 31. Finishing the concentric pot assembly

Note: The team found that the inner pot floated on top of the molten erythritol, so the weight must be heavy enough to push the pot into the liquid erythritol. The team used a pint full of water to place in the pot. Alternatively, the pot itself could be filled with water.

9. Insert insulation and combined pot assembly into the foam cooler

> Install fiberglass insulation inside the foam cooler around the pot assembly. Use proper personal protective equipment (gloves and glasses) when handling fiberglass insulation to avoid irritation. The completed cooker with insulation and housing is shown in Figure 32.

(a) Concentric pot assembly inserted into cooler stuffed with insulation

(b) More insulation is added to the top of the concentric pot assembly before putting the lid on the cooler

Figure 32. Completed first ISEC prototype set up for testing

5.8 Test Descriptions

The team conducted three tests on the first prototype to gauge its performance. The team conducted two 1-liter boil tests on the prototype and one cooldown test on the prototype. All tests began with a charging process in which the device was powered to bring the PCM to its full charge temperature which can be thought of as its own unique test. Detailed procedures for each test can be found in Appendix O and a risk assessment describing potential hazards of the device can be found in Appendix P. In the following sections, a brief description of each test will be given.

5.8.1 Charge Test

The charge test for our first prototype was an assessment of the device's ability to completely melt the PCM and raise it to the desired temperature of 150 °C within 4 hours. This was accomplished by monitoring and recording the temperatures of the PCM using the installed thermocouples while power was supplied to the diode chain. The experiment continued until either the desired temperature was reached, or the bimetallic switch was triggered. All three tests on the first prototype utilized a DC power supply. The set up for the first charge test can be seen in Figure 33.

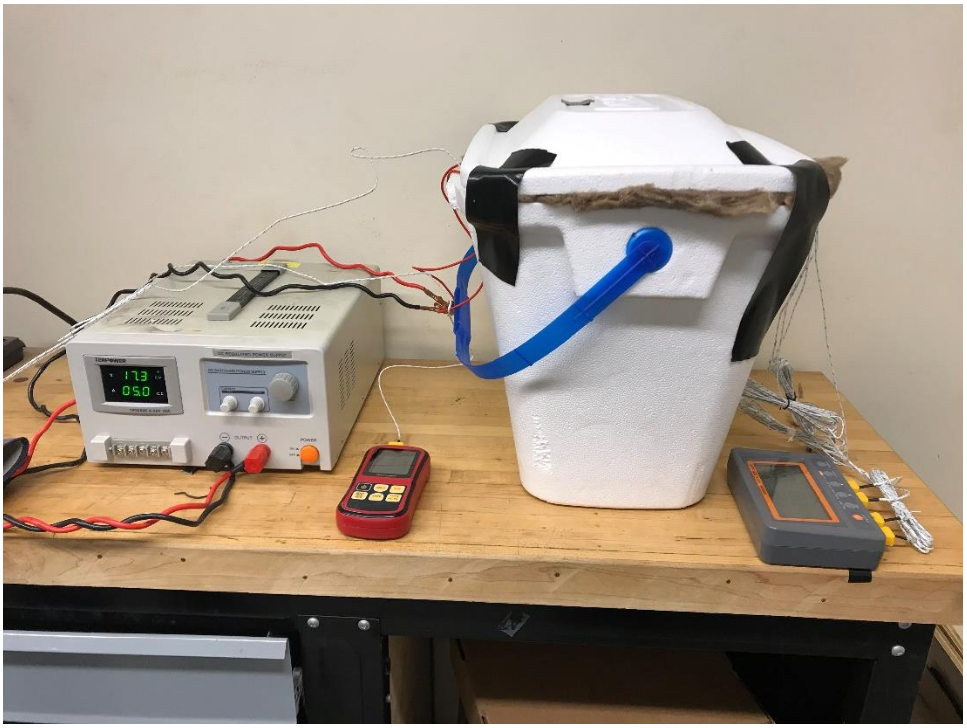


Figure 33. Charge test set up. The first ISEC prototype is displayed in the figure but the test set up remains the same for the second prototype also.

5.8.2 Boil Test

Two boil tests were conducted on our first prototype in order to identify how long it took the cooker to bring room temperature water to a boil. The boil tests consisted of adding room temperature water to the charged ISEC then monitoring the temperature of the water as well as the temperature readings of the embedded PCM thermocouples over time. The boil test setup can be seen in Figure 34. Both boil tests on the first prototype used 1 liter of water.

During the first boil test, our team choose to charge the device for 3 hours. In this first test, our team made the mistake of not recording the PCM temperatures after the water was added. In addition, we did not get a good visual confirmation on whether or not a full boil was achieved. As such, we felt repeating this test was worth-while.

On the second iteration of the test, our team also decided to use a different pot lid and to wrap the Styrofoam cooler in a sheet of soft insulating foam in hopes of achieving slightly better performance. In addition, our team also decided to charge the ISEC until the bimetallic switch cut off power after 3 hours and 51 minutes of charging to give our device its best possible chance at boiling the liter of water.

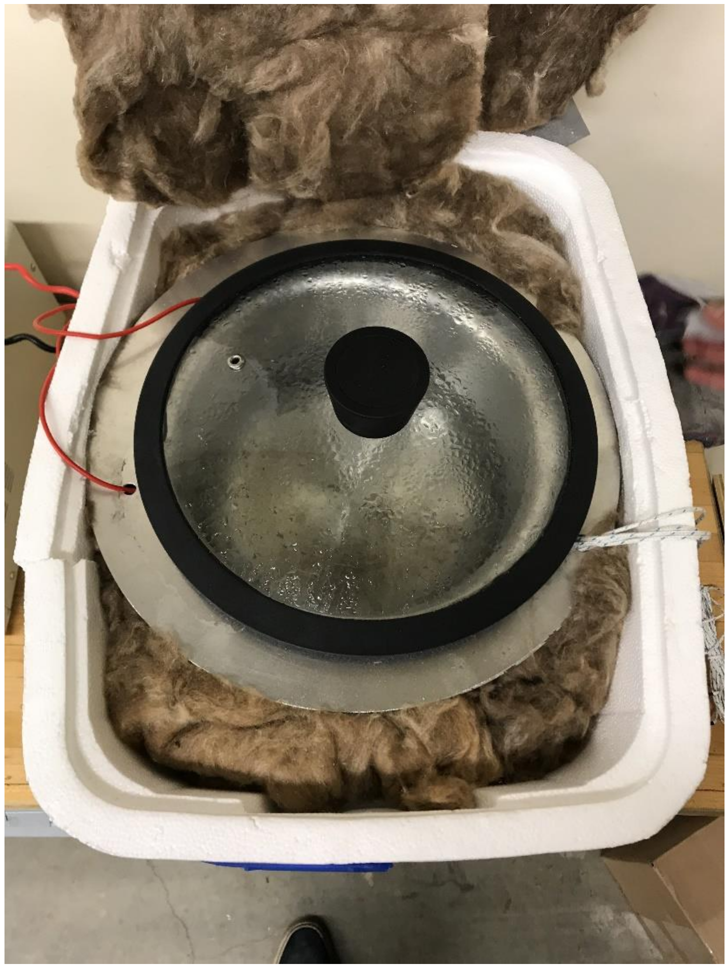


Figure 34. Boil test set up. The first ISEC prototype is displayed in the figure but the test set up remains the same for the second prototype also.

5.8.3 Cooldown Test

One cooldown test was performed on our first prototype. The cooldown test consisted of bringing the ISEC to a full charge temperature and then allowing the cooldown naturally in its insulation to ambient temperatures. The purpose of the cooldown test was to get a full picture of the heating and cooling curve for our PCM and to measure the effectiveness of our ISEC's insulation.

Having already completed our 1st boil test, our team already knew the Styrofoam cooler insulation system was quite insufficient to meet our project goals. As such, our team decided to test our ISEC in a 20-gallon trash can stuffed with fiberglass insulation instead. Our team planned to eventually use this trashcan as the housing for our second prototype and we wanted to test the insulation system before getting into our second build. For this experiment we allowed the ISEC to charge for 3 hours and 24 minutes at which point the bimetallic switch cutoff power.

5.9 Test Results - First Prototype

In this section, we will present test results from our three tests on our prototype

5.9.1 Charge Test Results

Figure 35 shows the results of the team's very first test. We were conservative when charging the ISEC because there was concern that the diode chain could pop or that the solder could melt at high temperatures. In this test, the ISEC was only charged for 3 hours. In future tests however, the team realized it was possible to charge the ISEC to a much higher temperature.

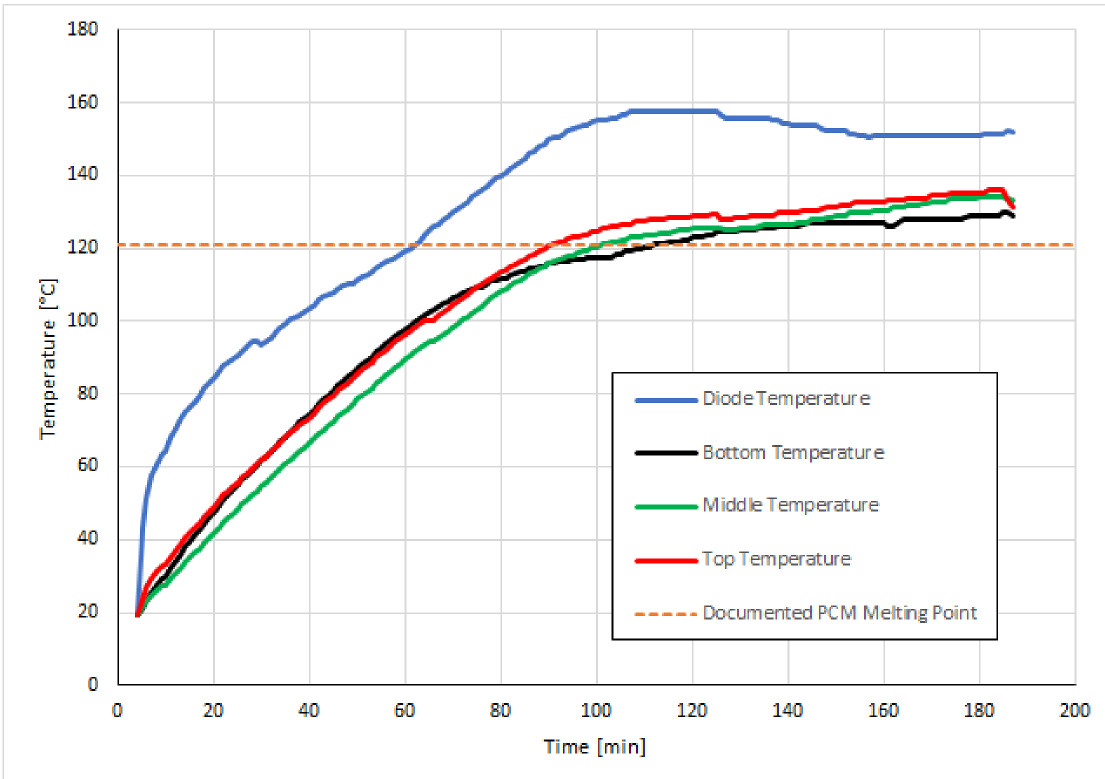


Figure 35. First prototype charge test 1 results

Shown below in Figure 36 is the second charge test that was conducted by the team. This time, the ISEC was charged until the bimetallic switch cut power after 231 minutes (nearly 4 hours). In order to verify that the PCM was entirely melted, the team opened the cooker and inserted a temperature probe into the PCM chamber. The team felt liquid in most of the cavity with some grainy inclusion at the bottom. The decrease in temperature around the 190 minute mark was due to heat loss from a physical observation by the team that involved opening the lid. The sharp decline in diode chain temperature at the end of the test was caused by the bimetallic switch kicking on and opening the diode chain circuit.

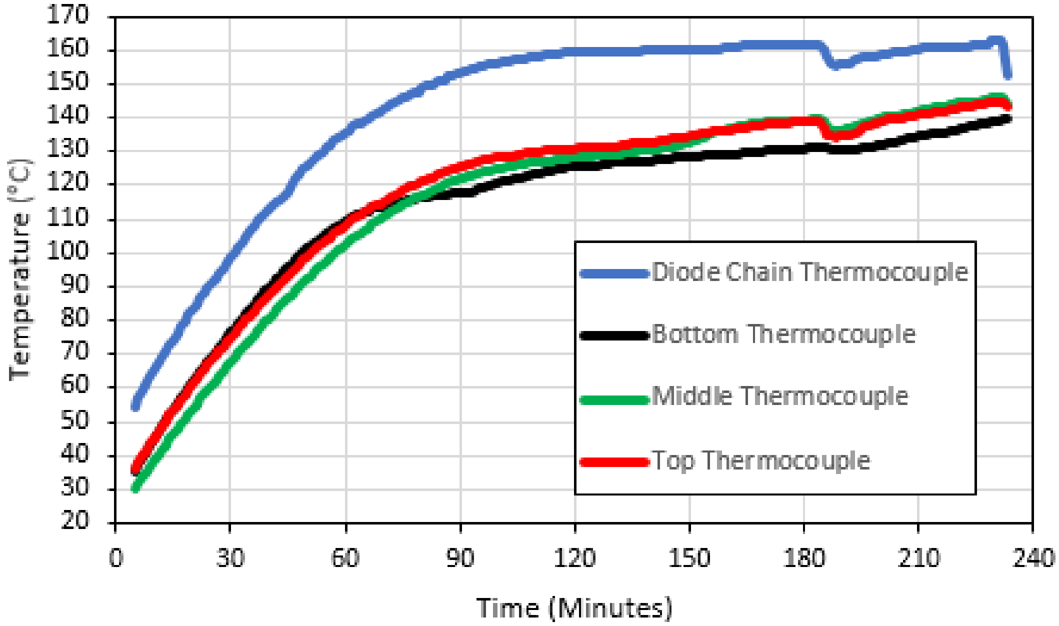


Figure 36. First prototype charge test 2 results

5.9.2 1-Liter Boil Test Results

As seen in Figure 37, the team was able to obtain a faster boil time for the second test than the first. The main difference, and by far the most impactful on these results was caused by the fact that we charged the ISEC for approximately 50 more minutes for the second test than the first (233 minutes versus 183 minutes) which allowed the PCM to reach higher temperatures throughout the cavity. The second test reached boiling around minute 30 versus the previous test where boiling was not reached until about minute 40.

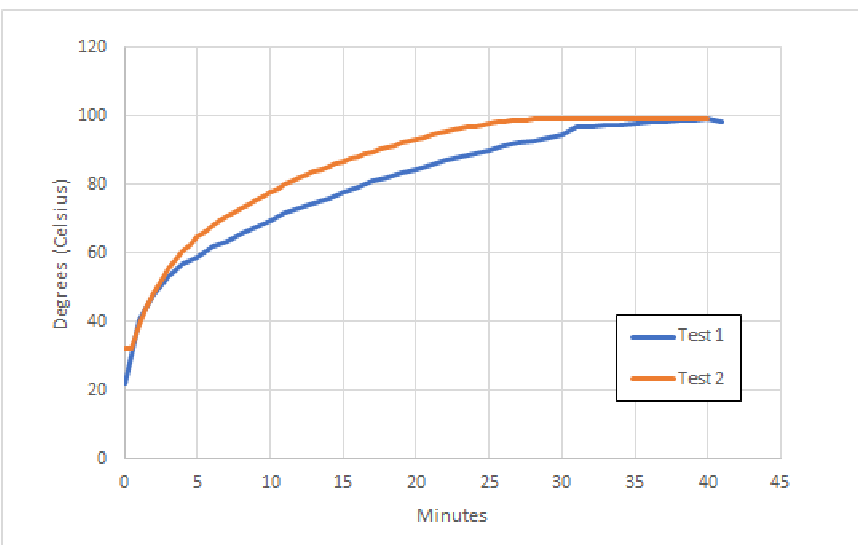


Figure 37. Comparison of Boil tests 1&2 for the First Prototype

In figure 38, we can see all thermocouple data during the boil test as well as the calculated power delivered to the water. We see that when the water is initially added to the ISEC, the PCM temperature rapidly decreases. We also see that the power delivered to water is initial quite high but rapidly decreases as the temperature gap between the water and the PCM is decreased.

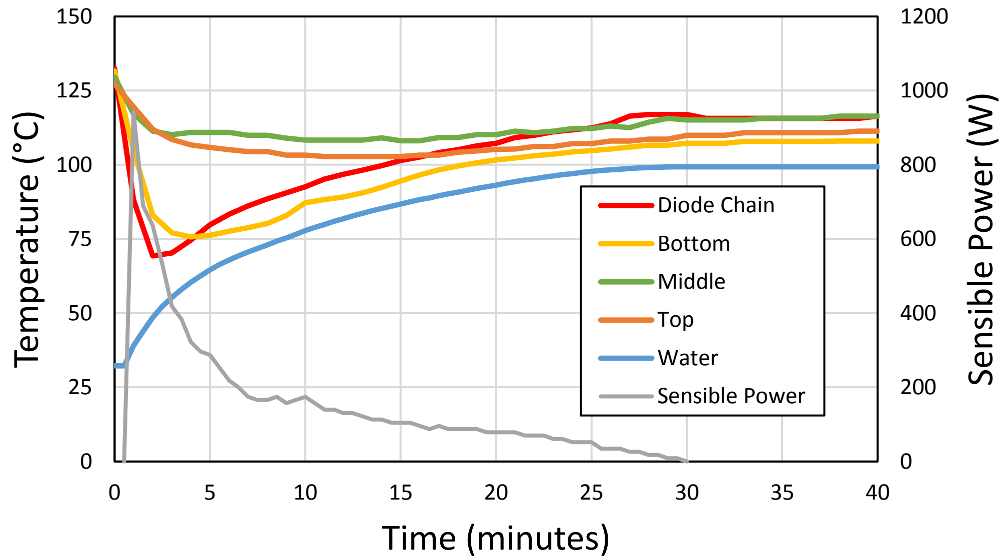


Figure 38. Detailed boil test 2

5.9.3 Cooldown Test Results

The range of temperature data for the cooldown test can be seen in Figure 39. From this data, we were able to calculate an R-Value of 8.03[K/W]. We were also able to estimate that only 72% of the erythritol was melted when the bimetallic switch cutoff power. This analysis can be seen in Appendix Q.

During the second boil test, after the bimetallic switch cut off power, we allowed the datalogger to record temperature data for a few minutes of cooling before adding the water. These data points can serve almost as a mini cooldown test for the foam cooler insulation system. The datapoints are shown in Figure 40. From these datapoints, we calculated the foam cooler insulation system only had an R-Value of [1.1K/W] which meant that at maximum temperature nearly 100% of energy being supplied to the ISEC was being lost to the environment.

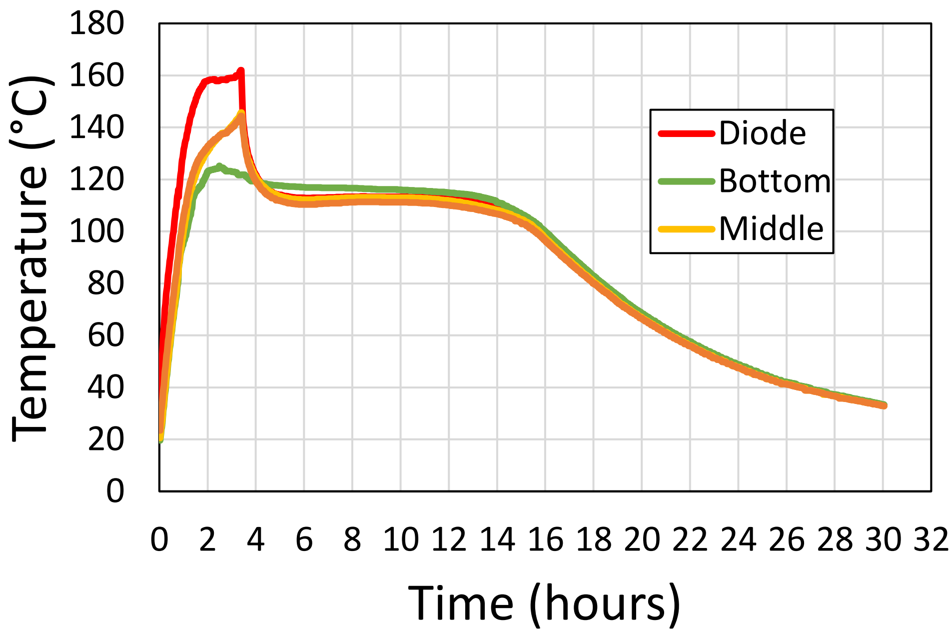


Figure 39. Cooldown test of the first prototype

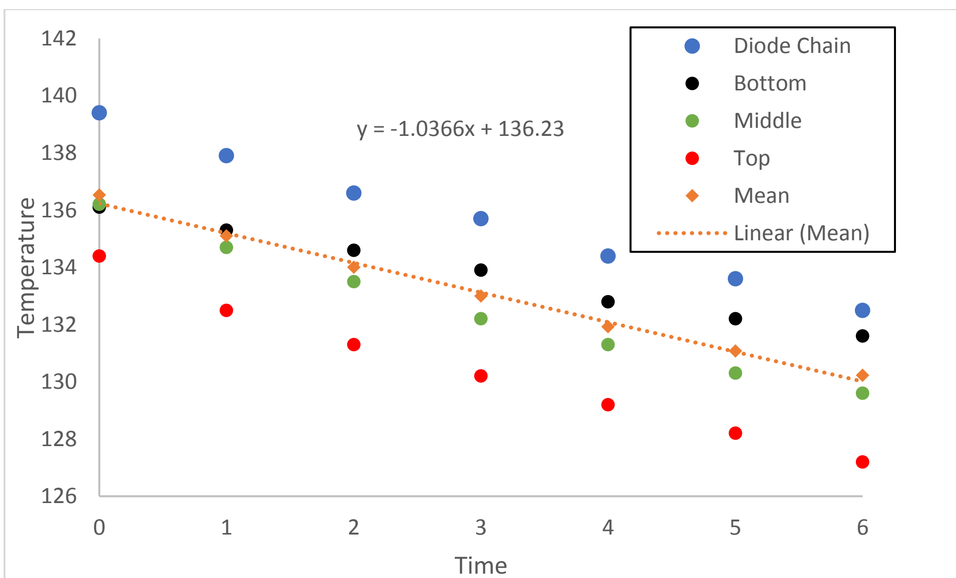


Figure 40. Cooldown data from boil test 2

5.10 Lessons Learned

A main area of improvement that the team immediately realized was the implementation of improved housing and insulation for the ISEC. For the first prototype, the team used a rectangular foam cooler and since the device is cylindrical, a housing that was more form fitting with the ISEC was ideal. For the second prototype, the team switched to a cylindrical housing that would allow for more insulation around the cooker.

Another improvement that the team considered of the utmost importance was to get more heating towards the bottom of the PCM cavity. It was determined that erythritol melts initially around the diodes, and then from the top to the bottom of the cavity due to convection patterns and differences in density between solid and liquid erythritol. With this issue in mind, it was obvious that the diode chain needed to be shaped differently to allow better heating at the bottom of the PCM cavity.

Finally, the team found that the bimetallic switch was cutting off power early, before the PCM was fully melted and well before the diodes had reached a potentially damaging temperature. To remedy this, the team chose to place the bimetallic switch farther away from the diodes so that the switch would cutoff when the diodes were hotter and the PCM was hopefully fully molten.

6 Design Changes for Second Prototype

After the critical design review, the team created a second ISEC prototype that included major design changes to the diode chain and housing as well as some other general improvements. Some of these changes included different parts and suppliers from the first prototype. The team created an updated bill of materials and suppliers list to reflect these changes. These can also be seen in Appendix R.

6.1 Diode Chain Revision

To improve functionality and adaptability to weather conditions, the team increased the amount of ground leads on the diode chain from one to three. The first ground lead is connected at the end of the diode chain and the others two are connected before the previous diodes. This gives the user the option to use either 22, 21, or 20 diodes in the diode chain. Varying the length of the diode chain effectively changes the voltage drop across the chain which can better match the voltage supplied by the solar panel if the cooker is connected to a different panel or if the cooker is used in suboptimal conditions.

Additionally, the shape of the diode chain as it was wrapped around the pot has been modified. From the first prototype, it was discovered that the erythritol at the bottom of the pot was having difficulty melting. It was then decided that JB welding a part of the chain directly to the bottom of the inner pot and then looping around the bottom fillet would be a better course of action. Not only is the diode chain on the bottom of the pot, but the diodes are bent away from the pot so they rest deeper in the erythritol. Melting all the erythritol is a major priority and the team knew that this change needed to be made to improve the overall heating of the PCM cavity.

Also, the bimetallic switch was placed after the 11th diode (halfway throughout the chain) instead of at the end. To determine a more accurate representation of the average erythritol temperature, the switch was also angled downwards towards the bottom of the exterior pot. On the first prototype the bimetallic switch was much closer to the top than the bottom, and the top was overall much hotter which caused the switch to cut off early.

These updates allowed for much more efficient charging. The team also decided electrical connection between the diode chain and pot was a concern for this new diode configuration. To electrically insulate the diode chain from the pot and prevent an electrical short, the team applied a thin layer of JB weld around the trace of the diode chain. This JB weld trace was left to dry before the diode chain was installed on top of it. These changes are reflected in Figures 41 and 42.

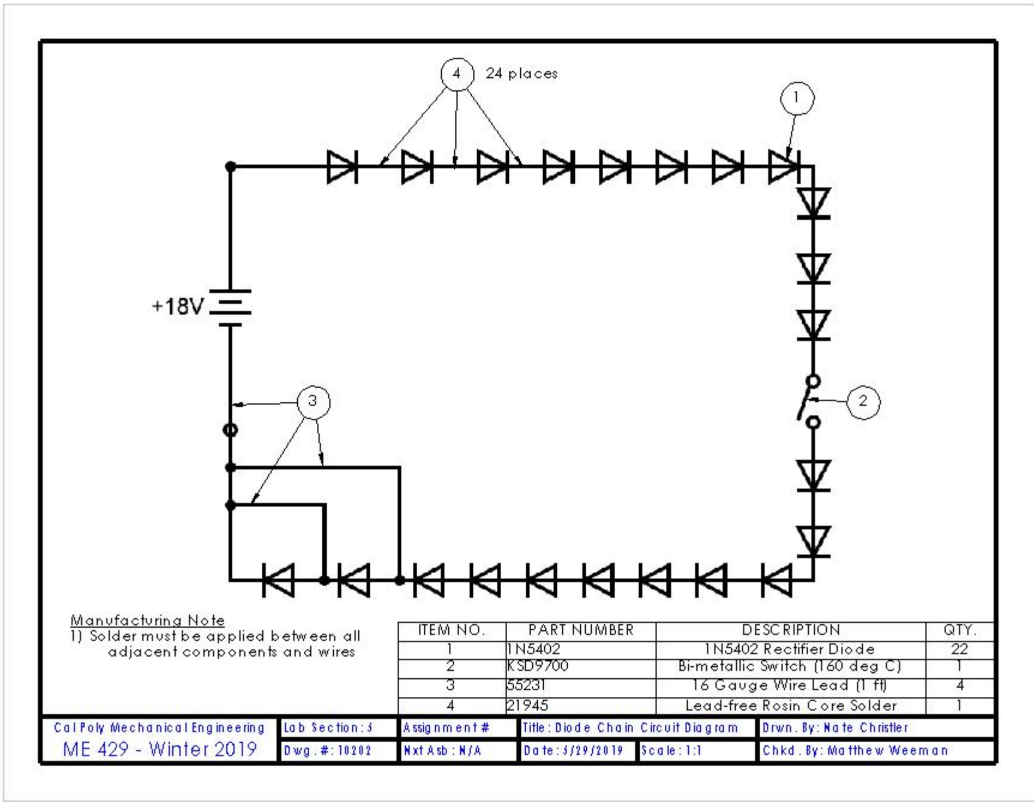


Figure 41. Circuit diagram of prototype 2 diode chain

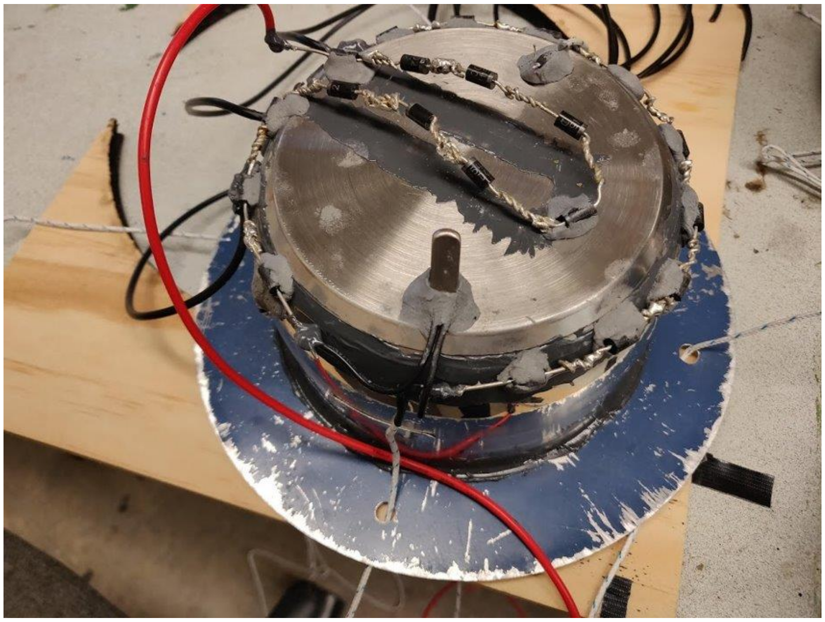


Figure 42. Orientation of revised diode chain and bimetallic switch for the second prototype

6.2 Housing Revision

Another major design revision is the housing that contains the insulation and cooker subassembly. Rather than use a rectangular housing, the second prototype utilizes a cylindrical housing that better matches the cylindrical cooker assembly. Cylindrical housing removes any thin spots in the insulation and allows for consistent insulation thickness around the perimeter of the cooker. The revised cooker housing is displayed in Figure 43.

Figure 43. Cylindrical housing for the second ISEC prototype. At this point in the manufacturing, the housing has already been cut in half and edges have been filed and taped.

Along with the updated housing, the team has completely isolated the insulation from any other part of the cooker. To accomplish this, the team made another flange extension, this time from the exterior pot to the cylindrical housing. The outer flange extension isolates the bottom insulation from the cooker and provides a rigid housing for the concentric pot assembly to sit in. The bottom housing flange extension is shown in Figure 44. Another part was made as a flat cap for the top half of the housing to isolate the top insulation from the cooker.

Figure 44. Flange extension between exterior pot and housing with a cavity to hold the concentric pot assembly

6.3 General Improvements

Other improvements to the ISEC include a different selection of pots and mass of erythritol. New pots allowed the team to use a larger amount of erythritol; approximately 2.27 kg as opposed to the 1.80 kg used previously. More erythritol means the cooker will take longer to charge but will have a greater amount of thermal energy storage. This additional thermal storage will greatly increase our cooking capacity as well as greatly improve our cooking time.

7 Second Prototype Manufacturing

With an improved design finalized, the team moved forward with manufacturing of the second prototype. What follows is a detailed discussion of material acquisition and associated costs, a step by step guide to manufacturing the second prototype, and a subsequent discussion of the difficulties the team faced with recommendations on overcoming them.

7.1 Material Acquisition and Cost Breakdown

The second prototype was considerably more expensive than the previous iteration, as shown in Table 5. This increased cost stems from replacing components used in the manufacturing of the first prototype, such as new pots or sheet metal, and the components necessary to improve the housing and insulation subassembly. While minimizing the cost of the ISEC was an important goal of the project, Dr. Schwartz encouraged the team to utilize the proof-of-concept status of the project to our advantage and spend the necessary funds to create a strong case for phase change material as a viable thermal storage system. That being said, there was still an abundance of materials, such as diodes and JB weld, available to the team from the previous ISEC projects that presented no increased cost for the team. These items are denoted by a "N/A" in Table 5. A fully updated budget and cost break down for the second prototype can be seen in Appendix S that includes tooling and testing equipment. All components were either ordered online by our sponsor or purchased from the local Home Depot by the team.

Table 5. Updated Cost of Second Prototype

Item	Cost	Cost to Us
Concentric Pots	29.99	29.99
Erythritol	17.25	N/A
JB Weld	23.04	N/A
Diode Chain	5.60	N/A
Aluminum Sheet Metal	13.99	13.99
Fiberglass Insulation	15.00	N/A
Cylindrical Housing	12.97	12.97
Velcro Strips	4.28	4.28
Nylon Strap	3.00	N/A
Metal Grate	9.37	9.37
Plaster Cloth	18.61	18.61
Subtotal	**153.10**	**89.21**
Solar Panel	80.00	N/A
Total Cost	**233.10**	**89.21**

7.2 Manufacturing and Assembly of Second Prototype

The steps taken to manufacture the second prototype are documented in Figures 45-64 and the following steps. The manufacturing process was divided into two subassemblies: the concentric pot subassembly and the housing subassembly. Unless otherwise specified, all manufacturing took place in Room 109 of the Bonderson Project Center. The accompanying engineering drawings to the following manufacturing steps can be found in Appendix T. A detailed user's manual describing how to operate the device one it is fully assembled can be found in Appendix U.

7.2.1 Concentric Pot Subassembly Manufacturing

1. Cut handles off pots

   The second prototype utilized new pots that had handles that would interfere with the rest of the cooker assembly. The team used a metal hack saw to cut the handles off the pots and then filed down the sharp edges.

Figure 45. Handle cut and detached from pot

2. Construct diode chain

The second prototype was constructed in a very similar fashion to the method described in Section 5.6.1. However, as mentioned earlier, the bimetallic switch was placed after the 11th diode. Once the diodes and bimetallic switch were soldered together, the main wire leads were soldered to the ends of the diode chain. Finally, the additional wire leads mentioned in Section 6.1 were soldered to the connection between the 20th and 21st diodes and the connection between the 21st and 22nd diodes.

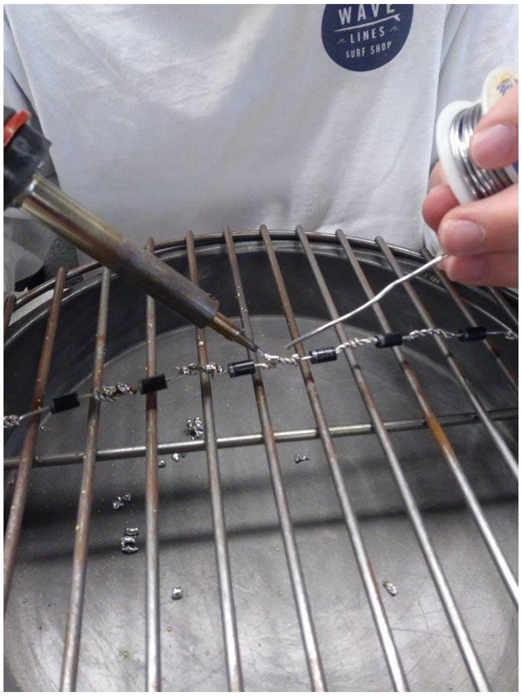
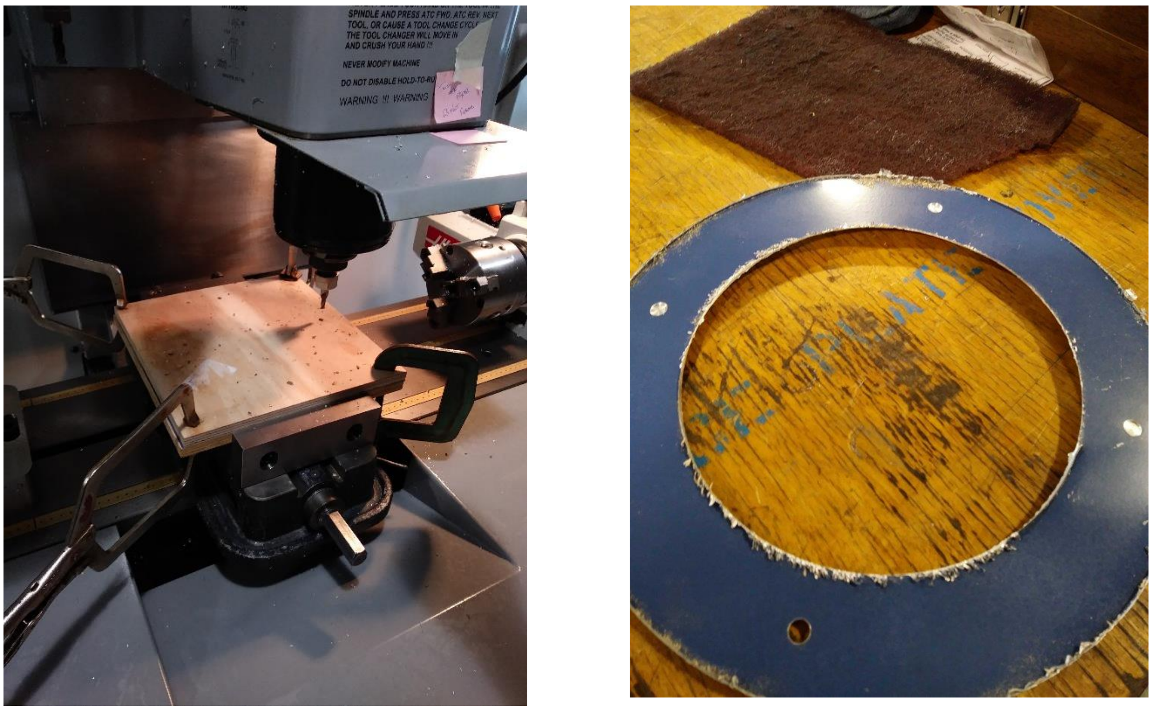


Figure 46. Soldering the already twisted diode leads

3. Cut flange extension and drill holes

When it came time to manufacture the second prototype flange extension the team was unable to access a functioning water jet cutter. As a result, this flange extension was cut on a Computer Numerical Control (CNC) Mill in the Advanced Machining Lab on the Cal Poly SLO campus. Due to the thickness of the sheet metal being so small, a sacrificial wood approach was necessary. This approach involves clamping the sheet metal between two pieces of wood and machining through the metal and wood. Clamping the sheet metal and wood together provides the necessary pressure to mitigate unwanted distortion in the sheet metal during the manufacturing operation



(a) Sacrificial wood technique inside a CNC mill

(b) Finished flange extension with large burrs and undrilled holes

Figure 47. Flange extension for the second prototype

4. Position the diode chain and trace the outline of the diode chain onto the internal pot with a pencil. Remove the diode chain and apply a 1 inch wide, thin layer of JB weld along the pencil trace to electrically insulate the diode chain from the internal pot.

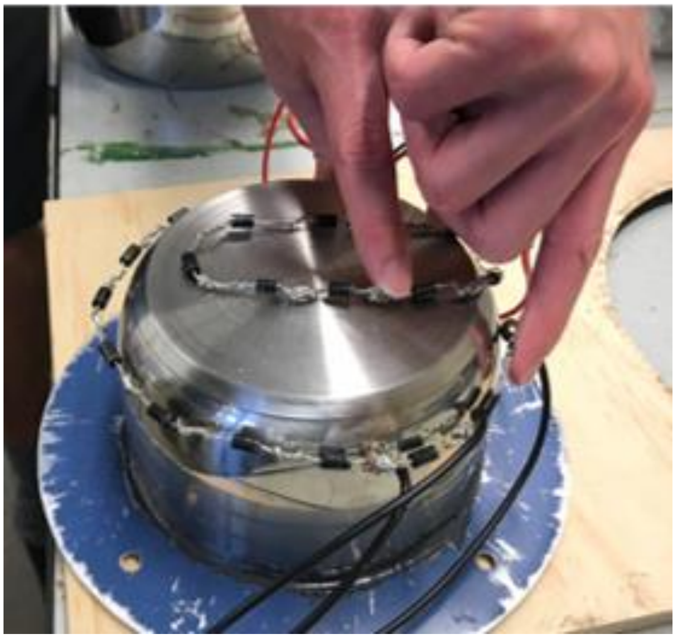


Figure 48. Positioning the diode chain prior to applying the JB weld trace

5. JB weld flange extension and diode chain to interior pot

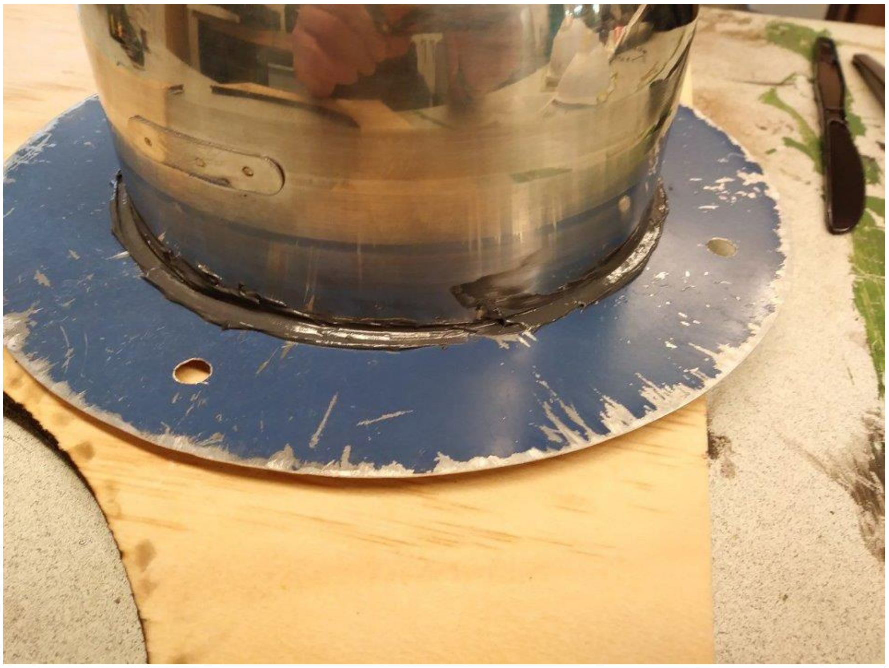


Figure 49. JB welding flange extension to inner pot

6. Run diode chain leads through hole in flange extension
7. Using JB weld putty attach all thermocouples to interior and outer pot

Figure 50. Middle thermocouple attached to the bottom of the interior pot (Only Middle Thermocouple Shown Here)

8. Measure and melt erythritol

   The team used an oven at one of the team member's house to melt the erythritol and finish assembling the concentric pots.

Figure 51. Measuring and melting of erythritol

9. Pour erythritol into exterior pot to fill the cavity between pots

Figure 52. Pouring the erythritol into the exterior pot

10. JB weld outer and inner pots together

Figure 53. JB weld placed on the top of outer pot and how the concentric pot subassembly was placed to dry

7.2.2 Housing Subassembly Manufacturing

1. Cut trash can in half using a jab saw and file edges
2. Drill a few drainage holes in the bottom of the trash can for any condensation that may occur

Figure 54. Holes drilled in the bottom of the trash can

3. Trace both diameters of the cut sides of the trash can on to the metal grate and cut out with wire snips

(a) Cutting out the metal grate along the trace of the trash can diameter

(b) Cutout of the metal grate placed on the top side of the trash can

Figure 55. Metal grate cut into a circle to fit onto the trash can

4. Trace the exterior pot diameter onto the bottom side grate and cut out with wire snips

   Ensure the trace is of the outer pot diameter and not the flange diameter. The pot should nest in the grate up to the flange but not fall through.
5. Cover the exterior pot in four layers of foil and place it in the hole in the metal grate

Figure 56. Covered exterior pot placed in the metal grate. The grate is up to the pot flange and is sitting upside down in this picture.

6. Dip plaster cloth in water then carefully drape over the foil wrapped inner pot and surrounding metal grate until roughly 5 full layers of cloth have been lain down

   Work on a clean acrylic sheet to minimize sticking. Let the plaster dry for at least 24 hours.

Figure 57. Applying plaster cloth to the covered pot and metal grate

7. Apply 5 layers of plaster cloth to the flat metal grate

   Let the plaster dry for at least 24 hours.

Figure 58. Plaster cloth applied to the flat metal grate

8. Trim off excess plaster from both top and bottom pieces using scissors and remove the foil from the pot.

(a) Dried plaster on the bottom piece

(b) Bottom piece after plaster has been cut along the metal grate and foil has been removed

Figure 59. Depiction of the dried plaster on the metal grate and the finished plaster piece

9. Apply 2 coats of high heat engine enamel to both sides of each plaster pieces

(a) Engine enamel on the bottom piece (b) Engine enamel on the top piece

Figure 60. Engine enamel applied to plaster pieces

10. Cut nylon strap approximately 4 inches to fit over the trash can interface

Figure 61. Nylon strap cut to length

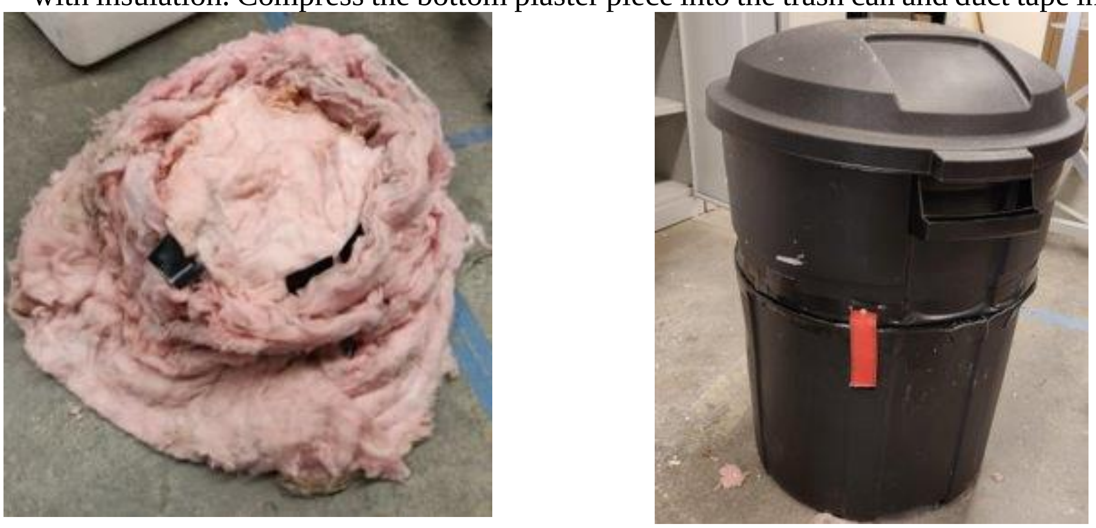
11. Apply one side of the Velcro to the bottom of the nylon strap and the other side of the Velcro to the matching location on the bottom half of the trash can
12. Use a rivet gun with properly sized washers to attach the nylon strap to the upper half of the trash can

Figure 62. Nylon strap attached to the top half of the trash can with a rivet and washer

13. Duct tape the upper plaster piece to the cut side of the top half of the trash can. Fill the trash can with insulation and attach the lid

Figure 63. Insulation stuffed into the top half of the trash can

14. Carefully wrap the lower plaster piece in insulation and fill the bottom half of the trash can with insulation. Compress the bottom plaster piece into the trash can and duct tape in place.



(a) Bottom plaster piece wrapped in insulation (b) Completed housing assembly

Figure 64. Final steps for assembly of the second prototype housing

7.3 Difficulties and Recommendations

It is very common to encounter unexpected difficulties and successes while manufacturing something for the first time. There were a number of these occurrence that the team believes merit discussion. First and foremost, machining the flange extension on a CNC mill was incredibly difficult. The end mill created large burrs on the edges of the flange extension and distorted the overall part. The team had to file down all edges of the flange extension and re-drill several holes before it could be attached to the inner pot. CNC machining of sheet metal is not recommended for future iterations. As mentioned in the initial discussion of the flange extension in Section 5.1.2, the requirements of this component limit the appropriate manufacturing methods. Until this component is eliminated from the design, some feasible alternatives include a sheet metal nibbler or metal hole cutter accessory for a hand drill.

The team also found soldering the additional leads onto the diode chain after the initial construction difficult. This hassle could have been avoided by twisting the additional leads between the diodes before soldering. These small improvements would have greatly improved the manufacturing process of the second prototype.

8 Design Verification

The team has performed testing on the cooker to determine the success of the final ISEC with thermal storage prototype. The planned testing included a charge test, a boil test, a cooldown test, and an efficiency test. These tests were conducted under ideal conditions and under actual solar conditions. All ideal testing was completed with a DC power source in Room 109 of the Bonderson Project Center. Actual solar testing took place at the project sponsor's house utilizing his 100 Watt PV panel station. A detailed design verification plan that describes the parameters tested and test criteria can be found in Appendix O. What follows are the testing results for the second prototype and a discussion of a possible source of error within these tests due to interference between the thermocouples and the thermocouple reader.

8.1 Second Prototype Test Descriptions

A total of six tests were performed on our second prototype. Two tests, a 1-liter boil test and an efficiency test, utilized solar power. Four tests: a 1-liter boil test, an efficiency test, a cooldown test, and a calibration and cook test utilized an ideal power source.

8.1.1 Boil Tests

The first test we conducted on our second prototype was a 1-liter boil test with the DC power source. This test was very similar to the 1-liter boil tests performed on our first prototype. We allowed the ISEC to charge for 5 hours and 19 minutes at which point we added the water to the ISEC. We did not turn the power off for this test until 5 hours and 55 minutes.

We conducted another 1-liter boil test using solar power. For this test we allowed the ISEC to charge from 9 AM until 4:20 PM, essentially one full solar day.

8.1.2 Cooldown Test

The second test we conducted on our second prototype was a cooldown test. For the cooldown test, we tried to charge the cooker as long as we could in hopes of triggering the bimetallic switch. After a full 6 hours and 3 minutes the switch had still not triggered and we decided to cut the power manually.

8.1.3 Efficiency Tests

The team ran one efficiency test with the DC power supply. For this test we used ice instead of water, which we added incrementally. The power supply for this test was kept on for 6.4 hours, past the point in which ice was added. Our team chose to keep the power supply running for part of the experiment to analyze whether or not having the diodes running would increase the overall energy efficiency. Our hypothesis was that allowing the diodes to run would keep the erythritol from forming and insulative shell around interior pot and improve the overall efficiency.

Another efficiency test was run using solar power. During this test only one increment of ice was added. The charge cycle for this test was one full solar day. The ice was added to the ISEC when the last bit of solar power was tapering off.

8.1.4 Calibration and Cook Test

The calibration and cook test was the final test performed on our prototype. After noticing sudden jumps in temperature after powering off the diode chain, indicative of an electrical error, the team felt it was necessary to attempt a calibration test to investigate the cause. This calibration test required that we fully charge the ISEC. Our team decided we should use this charge cycle as an opportunity to attempt a cook test with food.

8.2 Second Prototype Test Results

Overall, the second prototype demonstrated a satisfactory increase in performance compared to the first prototype. It can be seen in all tests that, at the cost of a longer charge time, the second prototype was able to reach higher PCM temperatures and achieve more melting during charge. What follows is a detailed discussion of the testing results for the second prototype.

8.2.1 Solar Performance

The performance of the solar panel on the two solar test days can be seen in Figures 65 and 66. As expected, the maximum power point for both days occurred around 12:30 PM. This time period is known as solar noon which is the point at which the sun is at its highest. As implied by the distinction “solar noon”, this time period does not always align with chronological noon. The maximum power for the first test was 86 Watts and the maximum power for the second test was 104 Watts. The average power output for day one was 66 Watts and the average power output for day two was 65 Watts, both approximately 2/3 the panel’s rated maximum power of 100 Watts.

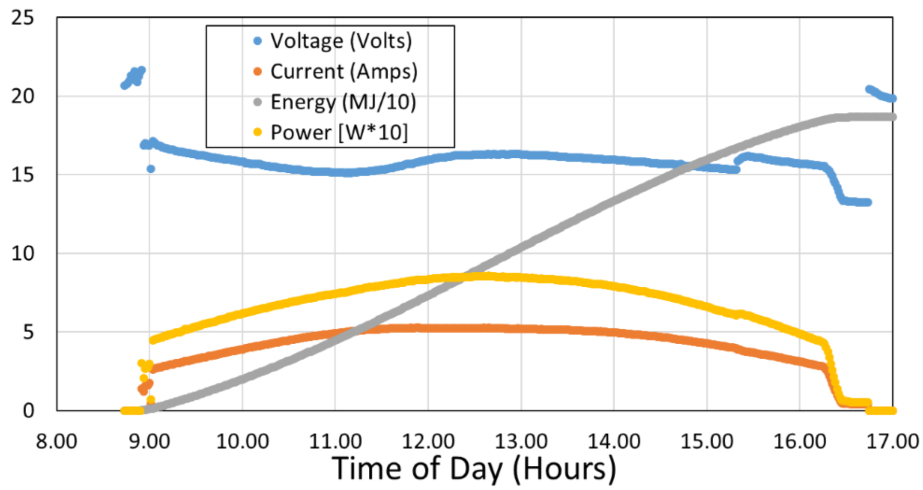


Figure 65. Performance of the 100 Watt Solar panel on May 14, 2019. Voltage was measured directly across the panels leads using a voltmeter. Current was determined by measuring the voltage drop across a small resistor with known resistance in series with the ISEC and using Ohm's Law. Both voltmeter measurements were recorded by a datalogger every minute for the entire duration of the test. Power was calculated by multiplying current and voltage, and energy was calculated by integrating the power with respect to time. The diode chain length was set to 20 diodes for this test. This day was clear and sunny.

As seen from the sudden drops in power in Figure 63, cloud cover does have a significant negative effect on panel power output. That being said, the total energy delivered to the ISEC on both test days was very similar at 1.87 MJ and 1.80 MJ for days one and two, respectively. One likely reason that day two still had a high power output was that we chose a diode chain length of 21 diodes as opposed to 20 diodes on day one. The choice to include another diode on day two put us closer to the optimal operating point for our panel.

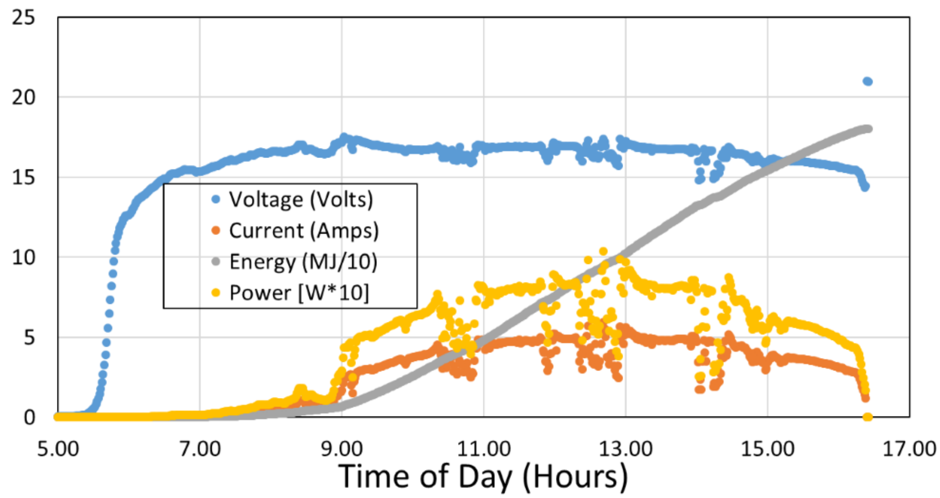


Figure 66. Performance of the 100 Watt Solar panel on May 16, 2019. The ISEC was hooked up to the panel the night before the experiment so the ISEC began receiving a small amount of power around 6 AM when sunlight first hit the panel. Significant power was not generated by the panel until around 9 AM when the sunlight was more direct. The diode chain length was set to 21 diodes for this test. The day was partially cloudy. The effect of cloud cover can be seen as the power dips throughout the day.

The total energies of 1.87 MJ and 1.80 MJ can be converted to 519 Watt-hours and 500 Watt-hours respectively. Both correspond to roughly 5 hours of ideal 100 Watt power which is slightly lower but still comparable to the ideal bench power supply testing. Figure 67 shows the performance of the ideal power supply over a 5.5 hour charging period. The total energy supplied is comparable to the solar tests at just under 2 MJ. As the energy in the solar tests is supplied over a longer period of time, a larger fraction of the energy will be lost to heat. This explains why our solar tests had a lower charge temperature and a lower efficiency overall compared to the DC bench power supply tests.

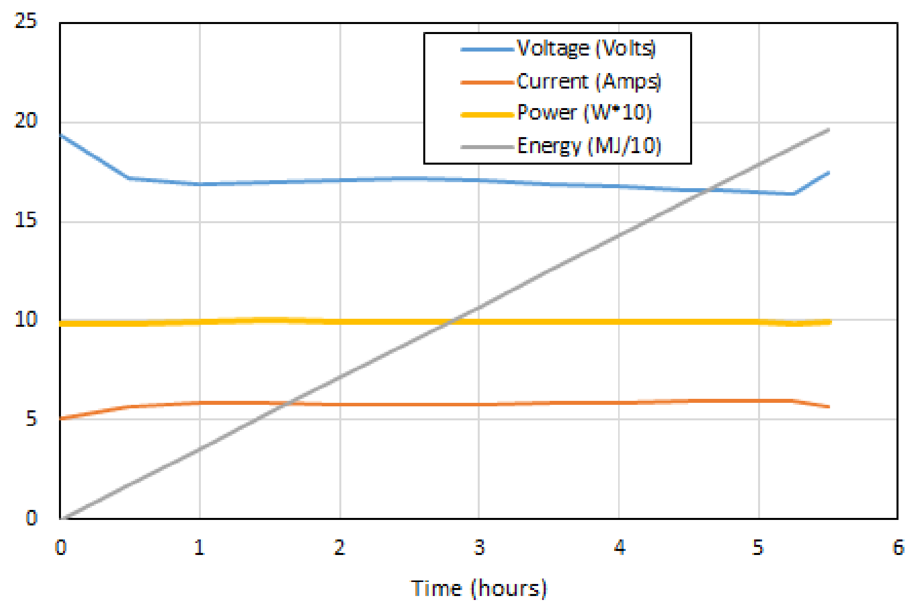


Figure 67. Performance of the ideal DC power supply for the 1-liter boil test. On every test with the ideal source, voltage was carefully adjusted over time to maintain a constant power output of 100 W. All tests that utilized the ideal source have nearly identical performance curves. Note that the required voltage drops slightly with time. This phenomenon occurs because the performance of the diodes can vary slightly with temperature.

8.2.2 Boil Tests

Our team conducted two 1-Liter boil tests on the second prototype. One test was conducted with an ideal power supply and one test was conducted with solar power. The data from the ideal power source 1-Liter boil test can be seen in Figure 68. The data from the solar 1-Liter boil test can be seen in Figure 69. A comparison of all 4 boil tests, conducted on both prototypes, can be seen in Figure 70.

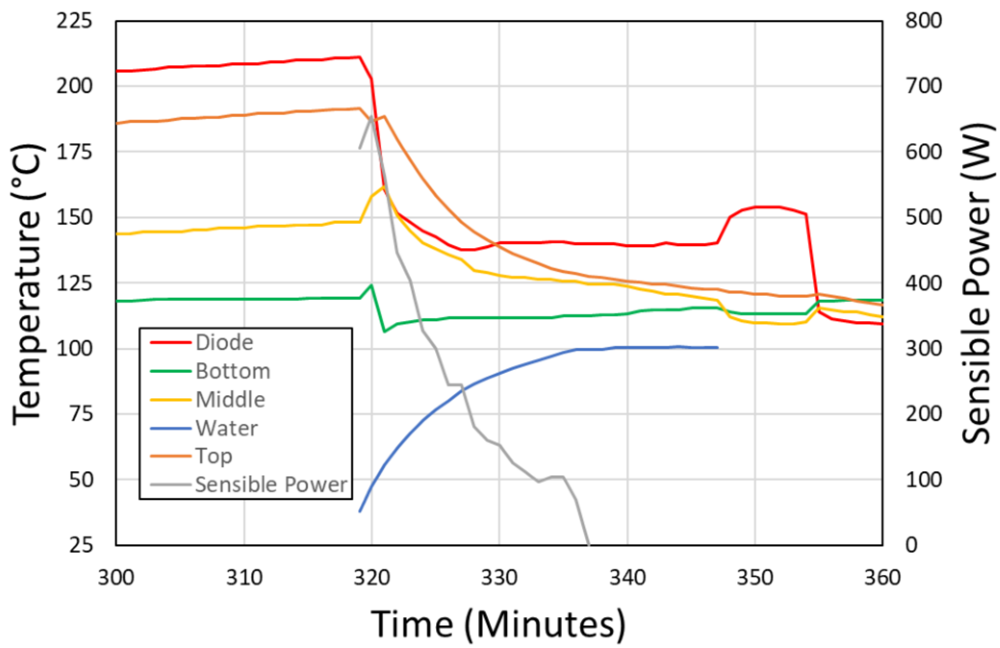


Figure 68. Boil test with ideal power supply

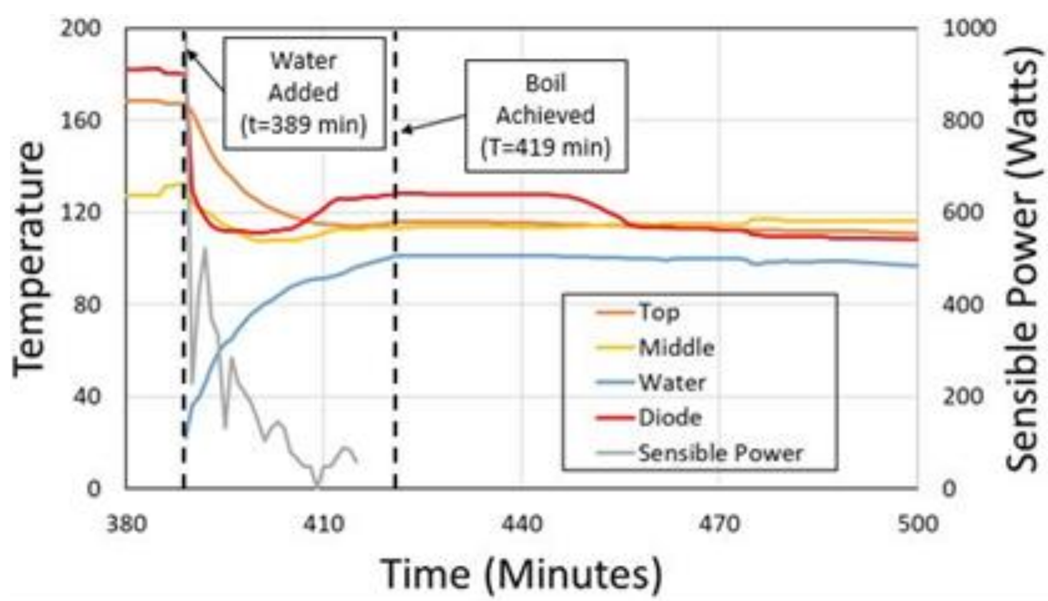


Figure 69. Boil test with solar panel conducted on May 14, 2019

The boil tests show that our second prototype is capable of bringing 1 liter of water to a boil in 18 minutes for the ideal test and 30 minutes for the solar test. This is a relatively short amount of time. The ISEC can maintain a boil for around 4 hours or longer. From the sensible power curves, we see that power is very high initially (600-1000 Watts) but decreases over time as the water increases in temperature and the PCM decreases in temperature.

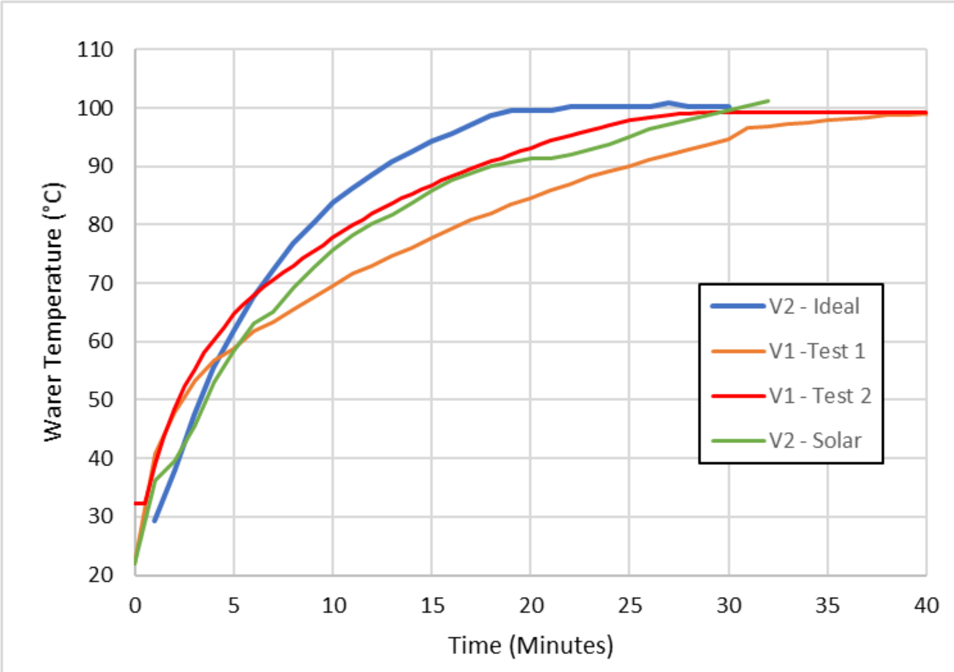


Figure 70. Comparison of boil tests between first prototype (V1) and second prototype (V2) with both solar panel and DC supply

When all shown on one graph, the improvements between the boil tests for the first prototype and second are clear. For our second prototype, the ISEC was able to achieve boiling in only 18 minutes and was boiling vigorously at the time. There was clear steam emanating from the ISEC after approximately 22 minutes through the test. This is in comparison to the first boil tests where the first prototype reached a light boil around 30-40 minutes.

8.2.3 Cooldown Results

The temperature data for the full duration of the cooldown test can be seen in Figure 71. In this figure, we can clearly see the full phase change process for both charging and cooling of the PCM. For the cooling portion of the curve, we can clearly see three distinct sections: liquid-state cooling, phase change, and solid-state cooling.

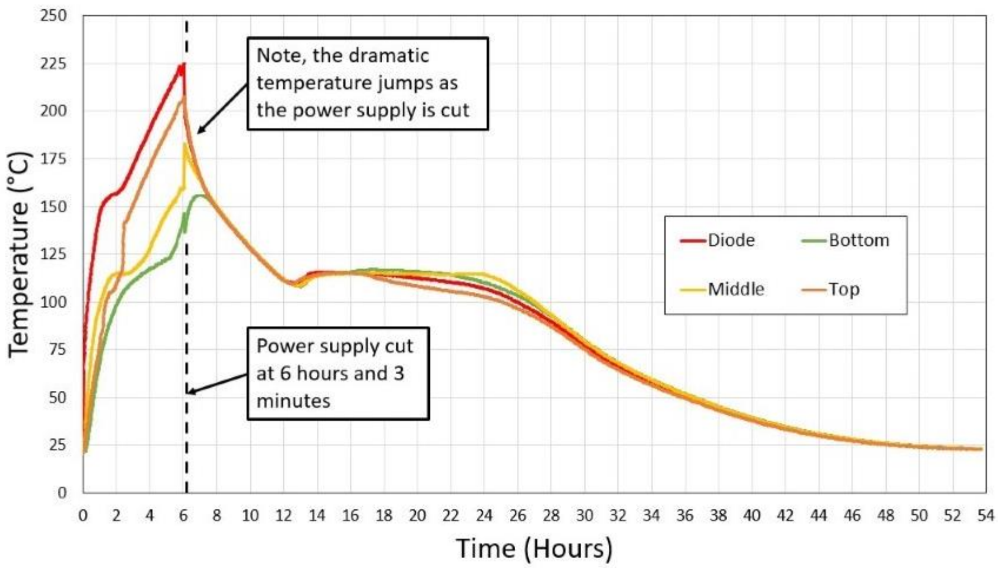


Figure 71. Cooldown test that was run until the PCM returned to ambient temperature

From a linearized plot of the solid-state cooling we were able to determine the R-Value of the device insulation, as seen in Figure 72. Similarly, we were able to determine the R-Value of the device from the liquid-state cooling, as seen in Figure 73. The R-value is used to characterize the relationship between temperature and power loss to through the insulation.

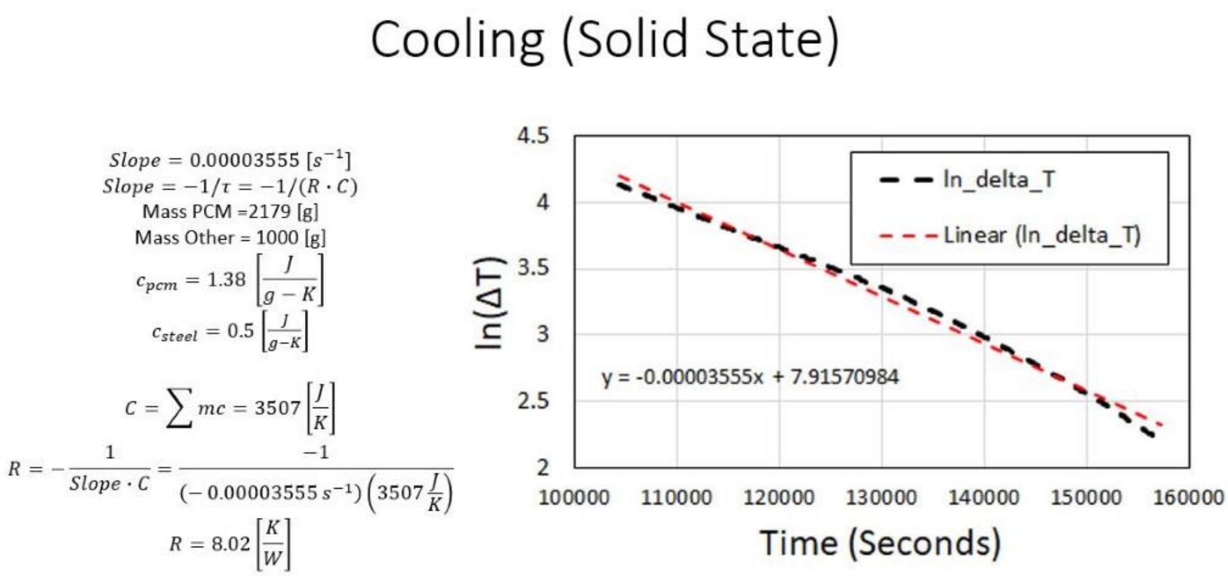


Figure 72. Showing how R-Value was calculated from the slope of the PCM cooling curve

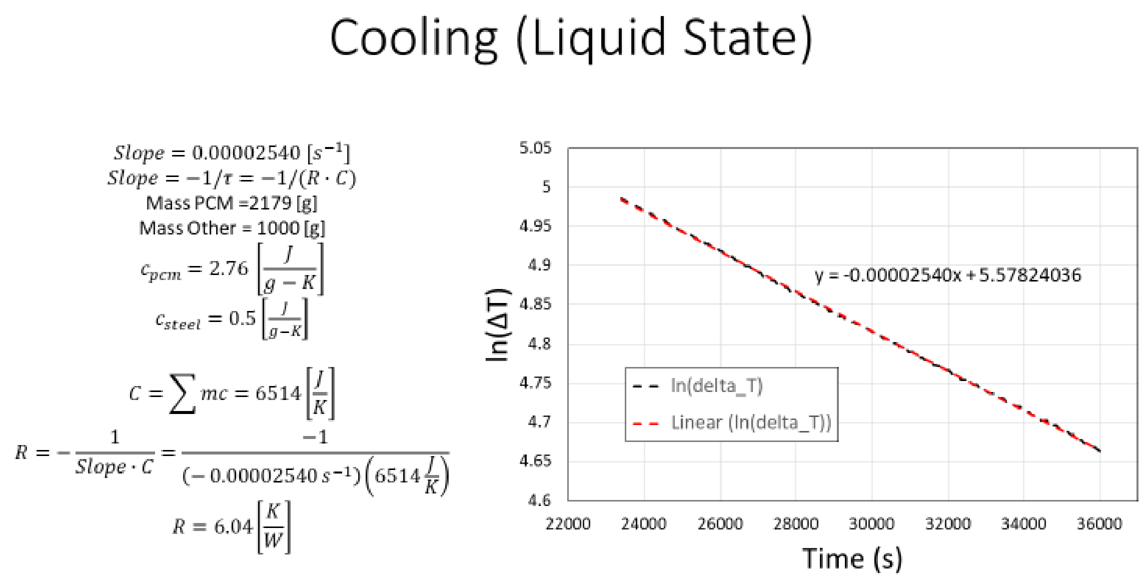


Figure 73. Liquid state cooling curve for second prototype cooldown test

For the solid-state cooling curve, we found an R-value of 8.0 K/W for the device. The R-value determined from the liquid-state cooling curve was slightly lower at 6.0 K/W. One possible reason why the R-value might be lower for the liquid state is that in the liquid state, convection can occur within the PCM which facilitates heat transfer and heat loss. Regardless, our team felt both these R-values were sufficient for our design. At a temperature difference of 150 °C, the R-values of 8.0 K/W and 6.0 K/W predict rates of heat loss of 19 Watts and 25 Watts respectively, which is quite manageable when compared to our design power of 100 Watts.

Using the R-Value from the solid-state cooling curve (a single R-Value was used for simplicity), we estimated the heat lost during each phase of the cooling process with the equation

$$q = (T_{pcm} - T_{amb})R$$

The cooling curve was then integrated with respect to time to determine the total amount of energy stored in each stage of the PCM cooling and the previously calculated heat loss was taken into account for each stage. This distribution of energy is shown in Figure 74.

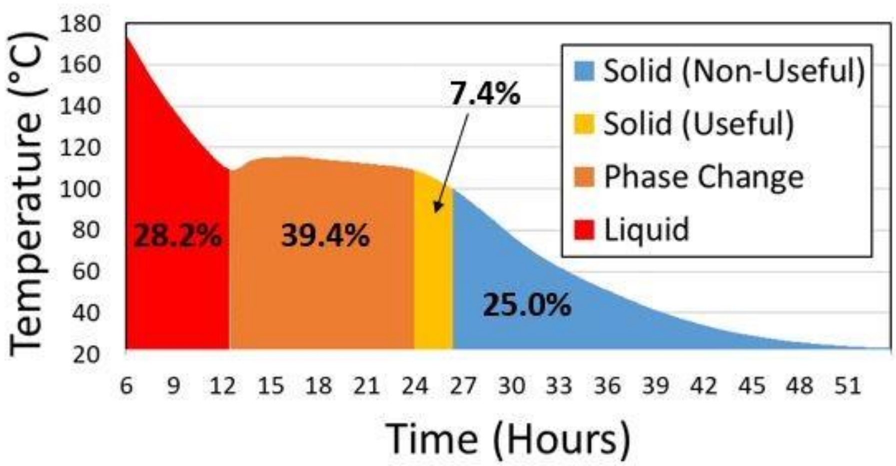


Figure 74. Graph showing percentage of useful versus non-useful energy. The results are derived from a PCM cooling curve. The useful energy is characterized by the PCM being above 100 °C because the heat can still be transferred to the pot contents to reach or maintain a boil.

These measurements of heat loss should also correspond to the distribution of energy storage at full temperature. For comparison, we also calculated the expected values for the energy distribution using documented values for the heat of fusion and specific heat for erythritol in both solid and liquid state. This comparison is shown in Table 6. In this expected value we also factored in the thermal capacitances of the other components of the concentric pot subassembly besides the PCM, which include the stainless-steel pots, pot lid, wires, diodes, JB Weld, and bimetallic switch. The combined mass of these components was 1000g and we estimated the specific heat of these components as that of 304-stainless steel at 0.50 J/(g−°C) [23].

Table 6. Comparison of expected and calculated energy stored in the ISEC

Storage State	Percentage of Stored Energy (Cooldown Test)	Percentage of Stored Energy (Expected)	Difference [%]
Liquid	28.2	24.8	3.4
Phase Change	39.4	49.6	-10.2
Solid (Useful)	7.4	4.6	2.8
Solid (Non-Useful)	25.0	21.0	4.0

All experimental values are within 5% of the theoretical value except for the phase change stage. Some possible explanations for the error are: that the single R-Value approximation is inaccurate, that the documented heat of fusion of erythritol was overestimated as a range was given for the heat of fusion and we chose to go with the midpoint of the range, or that there is a significant amount of erythritol that undergoes phase change within the liquid stage or solid stage cooling sections that hasn't been accounted for.

8.2.4 Efficiency Results

A new test, which was performed on our second prototype, was designed specifically to analyze the energy efficiency of our ISEC. In this test, a known mass of ice was taken from an ice water bath and then added to the fully charged ISEC. The ice melted within the ISEC and the temperature of this melted ice water would be measured and recorded with a spare thermocouple.

Ideally, the amount of ice added should be such that the final temperature of the water is near 100 °C but still below boiling. We wanted the final temperature of the water to be near 100 °C in order for the efficiency measurement to be a good gauge of our ISEC's useful efficiency for cooking via boiling and simmering. We did not want the water to boil as we did not have an accurate way of measuring the energy put into evaporated water. While we could attempt to determine the amount of water boiled off by measuring a difference in initial and final mass, such a measurement would likely be inaccurate due to evaporation, recondensation, and water loss when pouring the water from the ISEC into a new container for weighing.

The team chose to use ice from an ice water bath because preliminary calculations showed that even if the interior pot was filled all the way to the brim with cooled water, that water would still reach a boil. Similarly, the limited volume of our interior pot required that the ice be added in multiple stages. As the cubed ice melted, more room was made for additional ice to be added.

The temperature data from the ideal efficiency test can be seen in Figure 75 and the temperature data for the solar efficiency test can be seen in Figure 76. The efficiency for the solar test was determined to be 33% and the efficiency for the ideal test was determined to be 38%. Recall, the cooker efficiency is defined as the percentage of energy transferred to the food from the total amount of energy supplied to the cooker heating element. An uncertainty propagation analysis was conducted with respect to these efficiency values and an uncertainty of ±1.3% was determined. The hand calculations for this analysis are shown in Appendix V.

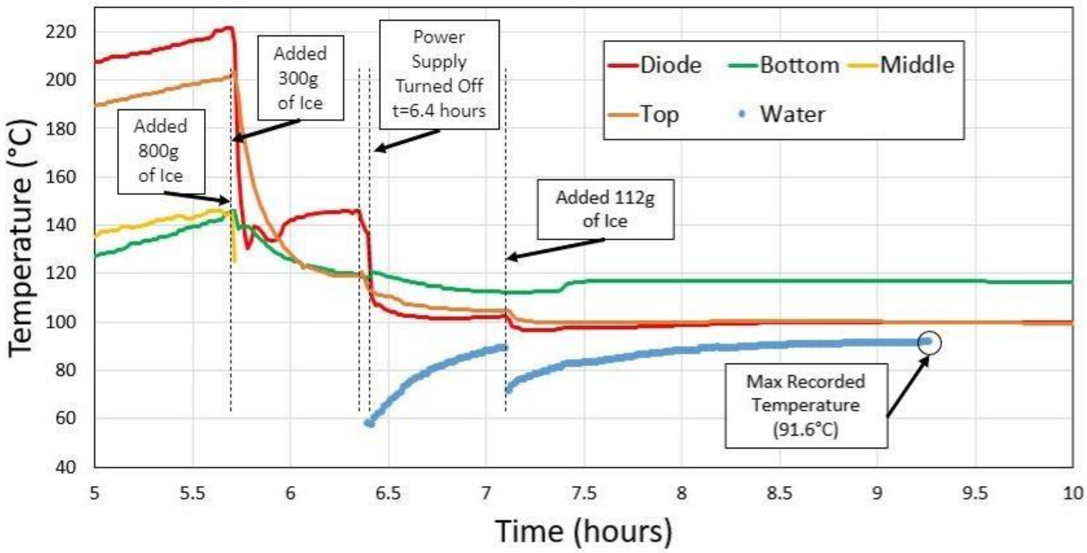


Figure 75. Efficiency test run with ideal power supply. The thermocouple reader was not recording properly after the first time the ice was added. The team checked the temperature of the water with a thermometer and added more ice when the temperature was approximately 92 °C. The first water curve probably looks very similar to the second. When the team added the second batch of ice, the water thermocouple was plugged in to a different port on the DAQ and began recording proper temperatures.

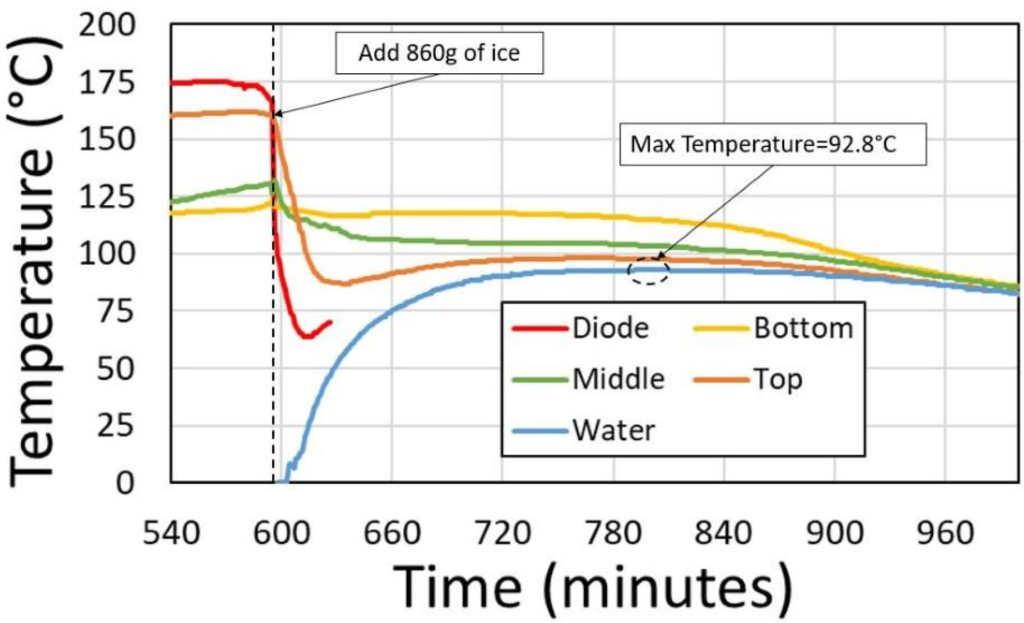


Figure 76. Efficiency test run with solar panel. The cooker was not charged as much in this test, so it only required adding ice once to prevent boiling.

8.2.5 Cook Test Results

After charging the cooker from the calibration test, our team decided to use the fully charged ISEC to cook a meal. Our team choose to cook a 226-gram box of Zatarain’s Red Beans and Rice. For this test, we added the rice mix along with 3 cups of water to the cooking pot and allowed the rice and beans to cook. We monitored the temperature of the rice and beans throughout the cooking process using a spare thermocouple and reader. We also stirred the mix occasionally throughout the cooking process to ensure it did not stick to the pot. Figure 77 shows the team cooking the red beans and rice.

Figure 77. Cooking red beans and rice in the ISEC

It took roughly 16 minutes to bring the mix and water to a boil, after which we continued to simmer the mix for 25 minutes. For comparison, on a stovetop the cooking process takes around 35 minutes.

After cooking the rice and beans our team dished it evenly amongst the team members and shared a meal. Taste tests confirmed that the food was fully cooked and turned out quite well. Within a few minutes all food had been eaten. Figures 78 shows the cooked food and Figure 79 shows the empty bowls indicating a job well done.

Figure 78. Food dished and ready to eat

Figure 79. Verification that food was fully cooked

After cooking, the team added water to the pot to let it soak. The next day the pot was cleaned by hand in a sink. The cleaning process, while manageable, was more difficult than a typical pot due to the loose wires, the wire holes to the PCM cavity (which we want to keep free of any contaminants), and the overall weight of the pot. Nonetheless, the pot was cleaned in less than 4 minutes.

8.2.6 Calibration Test

After analyzing the results for the second prototype, the team noticed an irregularity in the cooldown test, shown in Figure 71. At the 6-hour mark when the power was turned off, the temperature of the middle PCM thermocouple jumped up approximately 20 °C. The team at first could not explain this phenomenon. More testing with the thermocouples was conducted to try to repeat the results and explain what was happening. The team set up and charged the cooker, and while monitoring the temperatures, turned the power off and on at different temperatures throughout charging. This staggered data collection occurred once every 30 minutes, where the team would measure the temperature readings of the embedded thermocouples before disconnecting the power, after disconnecting the power, and then after reconnecting the power to determine how the readings differed with and without power. Specifically, the team collected data manually every 5 seconds for a minute before turning the power off, a minute after turning the power off, and a minute after turning the power back on. The 5 second data collection frequency was chosen to ascertain if the 1 minute data collection frequency of the data acquisition system (DAQ) being used by the team was incapable of capturing the entire phenomenon.

The team found the resulting temperature jump repeatable. Shown in Figure 80, there is a noticeable jump in temperature almost immediately following the power cut and reaches a steady state shortly after. This rapid approach to another temperature happens within 1 minute and would have been perceived by the DAQ as the straight-line jump. The temperature jump found was amplified at higher temperatures. When the cooker was half charged, the temperature jump was only 10 °C over the course of 20 seconds, but at fully charged temperatures, the jump was nearly 20 °C in 10 seconds.

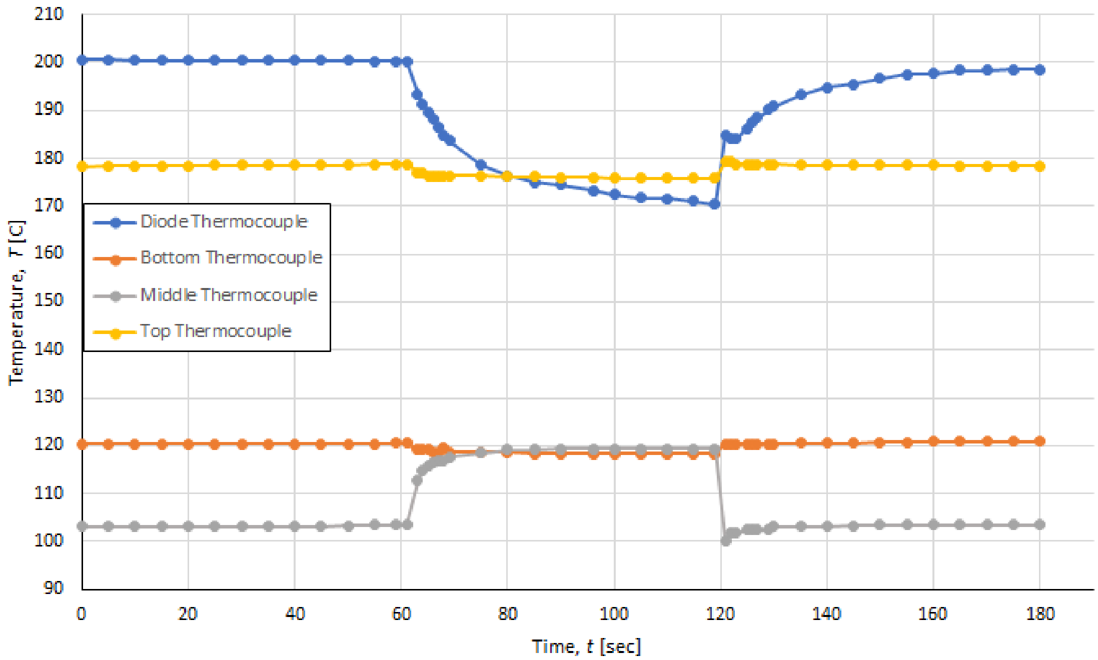


Figure 80. Thermocouple calibration test at full charge. Power was turned off at 60 seconds and turned back on at 120 seconds.

Our initial hypothesis is that the power source generated an electrical interference with the thermocouples and DAQ that was causing a low misreporting of higher temperatures and that the curve following the jump is the correct temperature. This hypothesis is further supported by a change in the temperatures in other channels of the DAQ when one thermocouple was removed from the DAQ. The team tested this as well by attempting every single combination of inserting the four thermocouples with both the power on and off. Throughout the test, there was temperature fluctuation in the thermocouples explaining the irregularities in the Cooldown and other tests. It was clear to the team that there was electrical interference between not just the DAQ and the power source, but inherent interference when there was more than one thermocouple hooked up to the DAQ. Unfortunately, the team discovered this late in the project during the second prototype testing and has only been able to capture the temperature discrepancy and the thermocouples' reaction. The team was unable to determine the root cause of this temperature jump.

While having incorrect temperatures readings is not ideal, it does not necessarily invalidate the data collected during previous tests. Many of the important tests and findings can be confirmed through other methods. During the boil test, we visually confirmed that the water was boiling. The efficiency test results are still valid as well because they depend on the water temperature and not the PCM temperatures. During the test, we verified the water temperature with another temperature probe. Also, the insulation R-Value depends on the slope of the temperature change, not any one temperature in particular. Regardless of interference, the rate of change of temperature will be constant, so the cooldown test remains valid as well. Though the figures with PCM temperature may not be exact, the results stemming from them remain true.

8.3 Results Summary

Overall the results that we found with our second prototype were highly promising. The ISEC could boil and cook at a speed that rivaled other more traditional cooking devices while at the same time maintaining an energy efficiency that is acceptable for the end users.

8.3.1 Meeting Design Specifications

Table 7. Results table for each critical specification

Specification	Desired	Result 1st Prototype	Result 2nd Prototype
Energy Efficiency	30%	27+/-1.3%	38.2+/-1.3%
Charge Time	2-4 hr	3-4 hr	4-5 hr
Time to boil 1L of water	20 min	30-40 min	18 min

In conclusion, our second prototype met the important design specifications of energy efficiency exceeding 30% and being able to boil 1 liter of water in less than 20 minutes, which were given to us by our sponsor, Dr. Schwartz. The team's sponsor is also aware of the increase in charge time and how it deviates from the original plan has still considered this device a success.

8.3.2 Overview of Meeting These Specifications

After not meeting our critical specifications with our first prototype, the team knew that improvements needed to be made. Clearly, the team succeeded with the second prototype. As explained above, the only issue that occurred was the need to charge the ISEC for slightly longer than we originally expected but Dr. Schwartz and Dr. Buskirk were on board with this direction. The updates of improving the diode chain and housing were proven successful. Future improvements to the ISEC to reach even higher efficiency and quicker boil times will be discussed further in Section 10.1.

9 Project Management

Throughout the project, the team remained aware of all the required steps and tasks for our senior design project. Utilizing a Gantt Chart, shown in Appendix W, the team knew the exact dates and deadlines to complete specific tasks. This was of the utmost importance since we were a part of a bigger overall group that consisted of interdependent ISEC projects as well as research being completed by individuals in the Cal Poly SLO Physics Department.

9.1 Design Process

As a team we completed all the objectives that were given to us by Dr. Van Buskirk and our sponsor, Dr. Schwartz. The team actively met with Dr. Schwartz and implemented his desired qualities to the ISEC. Having a regular, established meeting time with the sponsor was a great resource for the team and helped keep us on track and updated with design changes. Overall, everyone involved considered this project an absolute success from the guidelines and specifications given. However, there are ways that the team believes the device could be optimized which are explained in detail in the conclusion. During the design, manufacturing, and testing portion of our project, room D13 in the Science North building as well as the Bonderson Project

Center lab on campus were ideal areas to complete all our tasks. The team displayed all the progress that has been made on the project at the senior expo on May 31st, 2019.

9.2 Potential Unique Resources

Access to on campus laboratories for research and testing was given to the team and was utilized as a prototype assembly space and testing area. There were an abundance of diodes and wires supplied by our sponsor as well as an area to solder the diode chain in the building 52, room D13 research lab. Bonderson Project Center room 109 was the main area of overall assembly and testing due to the presence of a power source there that simulated the power of a solar panel.

9.3 Future Expectations

As the price of solar panels is dropping quite rapidly, this bears to mention that in the future, considerations will be made to the project to potentially switch to a more high-powered source. The trend of PV module cost with the increasing presence of solar energy is depicted in Figure 81. If within the next few years, there is a marginal cost decrease for a more powerful solar panel, the probability of this change is high.

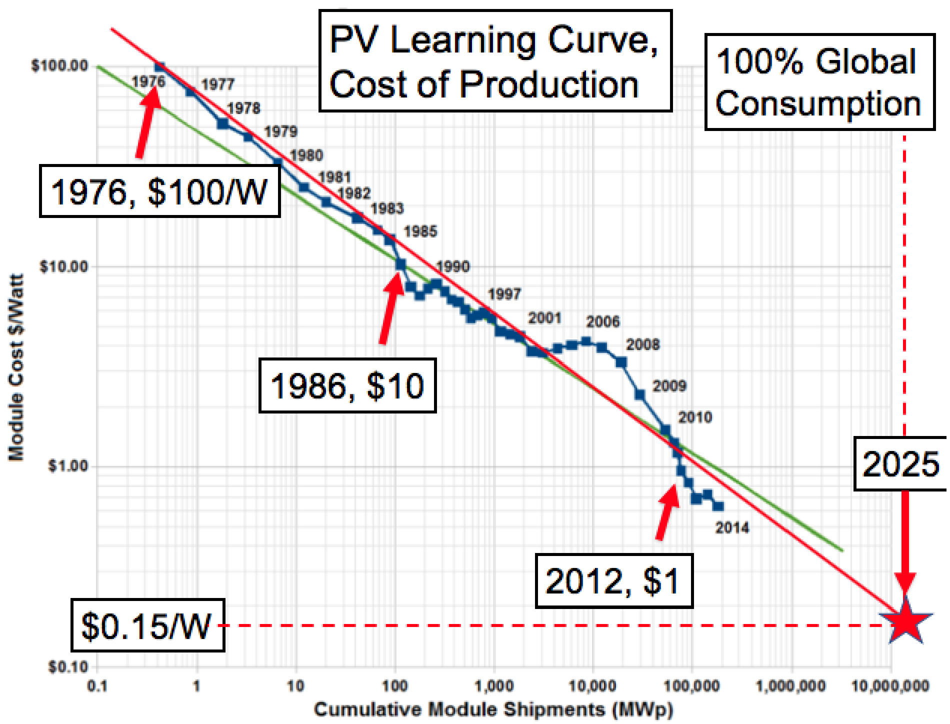


Figure 81. Plot of the cost of photovoltaic modules as production increases [14].

10 Conclusion

We have written this document in order to present our findings throughout the year for the insulated solar electric cooker with phase change thermal storage medium to Dr. Schwartz. From the results section earlier in the document, it is shown how the critical goal of boiling water in less than 20 minutes was successful. The team was able to reach boiling at 18 minutes. Additionally, one of the team's main goals was to have an efficiency greater than 30%. Recall the efficiency is defined as the amount of energy delivered to the food divided by the total energy supplied to the device. As the efficiency test showed, the team exceeded these expectations and was able to reach an efficiency of approximately 33% from a solar panel and a 38% efficiency from a DC power supply. More importantly though, this project proved that phase change thermal storage is a valid method of storing energy from a PV panel. With sufficient insulation, this thermal energy can be stored for days and can be utilized effectively to cook food and boil water.

The team did not create a product that is ready to be sold to consumers, but the project was still successful. The focus of the project was to help those in low income communities by creating a solar electric cooker for a low cost. In order to create a product that can be sold off the shelf, it would require more money to make a more polished, visually appealing cooker that can also be manufactured somewhat easily in bulk.

One of the biggest improvements that the team could have made was to improve conduction throughout the erythritol cavity. The team changed the diode chain placement in an attempt to fix this between the first and second prototype, however there could still be significant improvement. After seeing the results of the first prototype, Dr. Schwartz recommended optimizing the same cooker design without making drastic changes to how the cooker operates. The main reasons behind this suggestion were to keep manufacturability simple for communities in Africa and analyze the basic performance of this simpler design. This led to the second prototype consisting of an improved diode chain and insulation, but no changes in PCM selection or conduction assistance. Conduction assistance will be discussed in more detail in the next section where we outline the steps we believe need to be taken in order to have an even greater benefit for future testing.

10.1 Recommendations for Future Work

This project met the guidelines given and improved greatly upon the previous ISEC design. However, the team has noted several areas of improvement for future iterations of the ISEC with phase change thermal storage. The biggest future improvement that the team did not have time to implement would be to have some degree of conduction assistance throughout the PCM. While our second prototype did melt all the erythritol, the temperatures throughout the PCM cavity varied significantly from top to bottom. Increased conduction would hopefully allow more even and effective heating of the phase change material to achieve melting at a faster rate. Shown in Figure 82 below, is an idea for conduction assistance we had prior to manufacturing of the first prototype that was not selected.

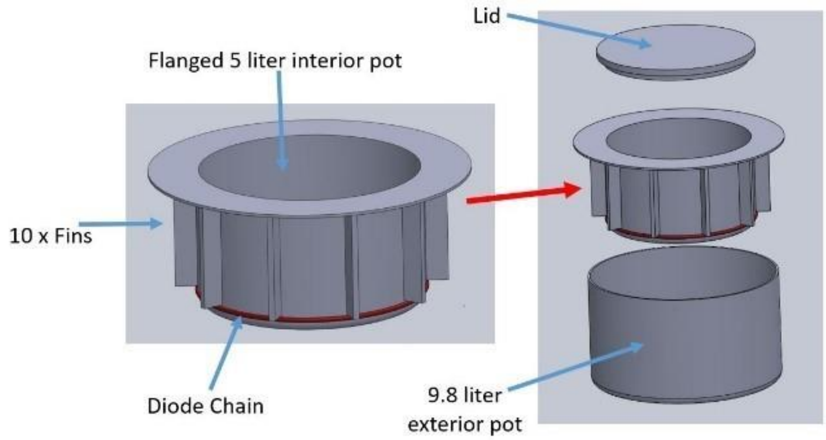


Figure 82. ISEC design using metal fins as conduction assistance

The team had brainstormed a design with ten evenly spaced fins around the inner pot. Although the team drafted a design with fins, this is not the only method of increasing conduction throughout the PCM. Other pieces of metal, such as aluminum shavings from a lathe or mill, included in the PCM will also promote conduction.

Another improvement to the device would be inclusion of chargers for other electronics as discussed in Section 2.4.1. Since diodes regulate voltage, more leads could be connected to the diode chain to provide the necessary voltage to charge cell phone batteries, electronic lights, and other small electronics. An improvement with a similar impact on end user desirability would be the consolidation of wires and sealing of the PCM cavity. The team frequently found the number of wires and length of wires difficult to manage, especially when moving the device. The team also found cleaning the device after cooking very difficult while trying to avoid getting food or water in the wire holes and PCM cavity. This could be resolved by a plug and port configuration within the concentric pot subassembly that allows all wires to detach from the cooker. Additionally, as mentioned in Section 8.2, if further testing is to be done with this device and the current DAQ, an in-depth error analysis will need to be carried out to determine and eliminate the source of interference between the thermocouples, the DAQ, and the power source.

In conclusion, the team feels that the insulated solar electric cooker with phase change thermal storage has been a success and a significant step towards the implementation of such devices in the communities we intend to serve. Dr. Robert Van Buskirk, who actively implements the previous ISECs in Malawi, explained how even though they will not be able to completely follow our manufacturing process in Africa, the people will find ways to substitute specific items and create an ISEC that closely resembles ours. The most important takeaway from this project is that these results prove cooking is possible with a solar panel, diode chain heating element, and phase change material. Hopefully, the findings that the team have made throughout this process can benefit others and improve upon their way of life.

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Appendix A: QFD House of Quality

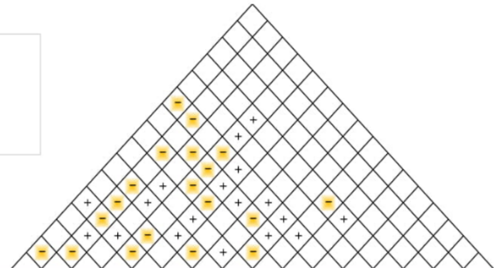
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Team 55 InSECTS
Revision Date: 10/15



WHO: Customers

Row #	Weight Chart	Relative Weight	Developing Communities	Manufacture and Transport	Peter Schwartz		Maximum Relationship	WHAT: Customer Requirements (Needs/Wants)
1		12%	10	4	10		9	Inexpensive
2		6%	6	4	2		9	Durable
3		10%	9	2	9		9	Quick Cooking
4		9%	5	7	3		9	Safe
5		9%	7	3	7		9	Non - Peak Hour Usage
6		8%	1	10	2		9	Ease of Assembly
7		5%	3	4	2		9	Ease of Cleaning
8		9%	2	8	6		9	Portable
9		9%	9	3	7		9	Cooking Capacity
10		4%	3	2	3		9	Ease of Use
11		9%	10	0	10		9	Standalone System
12		9%	10	0	10		9	Sanitary
13		0%						
14		0%						
15		0%						
16		0%						

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▲	▼	◇	▼	▲	▲	◇	▼	◇	▼	▲	▼	▼	◇	◇	
HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Charge Time	Total Cost	Max Temperature Internal	Weight	Thermal Efficiency	No Failure Under 400 N Force	Power (Watts)	Cook Time After Full Charge	Internal Volume	Max Temperature External	Liters of Water Boiled 1 Hour	Setup Time	Time to Clean	No Wax Contamination	No External Power	
Inexpensive		●		▽			▽				○					
Durable		▽		▽		●										
Quick Cooking		○	●		○		○	●	▽		○					
Safe		▽		▽						●						
Non - Peak Hour Usage	●	○	○		▽		▽	○	▽		●	▽				
Ease of Assembly		○		▽								●				
Ease of Cleaning				▽		▽			▽				●			
Portable		▽		●								○				
Cooking Capacity		○	○	▽	▽		○		●		▽					
Ease of Use		▽		○						▽		●	○			
Standalone System															●	
Sanitary														●		
HOW MUCH: Target Values	8 hours	140 Dollars	150 Degrees Celsius	30 Pounds	Maximize	Required	150 Watts	1 Hour	3 Gallons	Minimize (40 Celsius)	4 Liters	10 Minutes	5 Minutes	Required	Required	
Max Relationship	9	9	9	9	3	9	3	9	9	9	9	9	9	9	9	
Technical Importance Rating	76.73	244.5	140.6	146.9	46.87	63.09	77.67	112.4	108	81.52	151	150.4	58.46	82.25	82.25	
Relative Weight	5%	15%	9%	9%	3%	4%	5%	7%	7%	5%	9%	9%	4%	5%	5%	

Curr. Products

ISEC	5	4	2	5	3	2	2	1	5	3	2	3	5	5	5	
Competitor #1: Solar Oven	4	3	3	4	3	3	3	3	2	4	1	3	5	2	1	
Competitor #2: Parabolic	5	5	5	3	2	3	5	2	1	1	1	4	5	2	2	
Competitor #3: Rice Cooker	5	5	3	5	2	5	5	4	2	4	1	5	5	2	2	
Competitor #4: Pot Over Fire	4	5	4	3	1	3	5	4	5	1	1	2	3	2	2	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

NOW: Curr. Products

ISEC	Competitor #1: *Solar Oven*	Competitor #2: *Parabolic*	Competitor #3: Rice Cooker	Competitor #4: *Pot Over Fire*	Row #
6	6	10	7	9	1
5	6	3	8	5	2
1	6	9	8	3	3
4	6	2	8	5	4
1	4	1	10	10	5
5	3	6	10	6	6
5	5	10	3	3	7
7	4	10	5	8	8
6	7	2	5	8	9
6	5	7	9	7	10
					11
					12
					13
					14
					15
					16

Appendix B: PCM Comparison

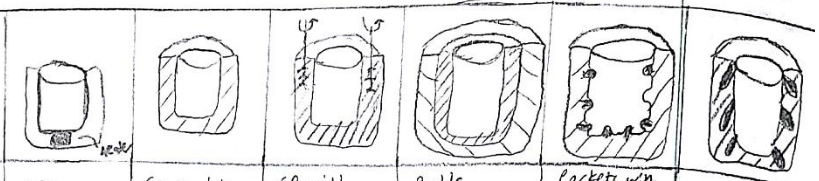
Property	**Units**	**Erythritol**	**MgCl2-6H2O**
Heat of Fusion	J/g	347	167
Melting Point	°C	118	117
Specific Heat (Solid)	J/g-°C	1.4	2.2
Specific Heat (Liquid)	J/g-°C	2.8	2.6
Thermal Conductivity (Solid)	W/m-°C	0.73	0.7
Thermal Conductivity (Liquid)	W/m-°C	0.33	0.57
Price Per Mass (Bulk)	$/kg	~2.00	~0.10
Corrosivity	N/A	Non-Corrosive	Potentially Corrosive
Food Safety	N/A	Safe/Edible	Safe
Electrical conductivity	N/A	Non-Conductive	Conductive
Supercooling	N/A	Large	Small

Appendix C: Decision Matrices

Pugh Matrices

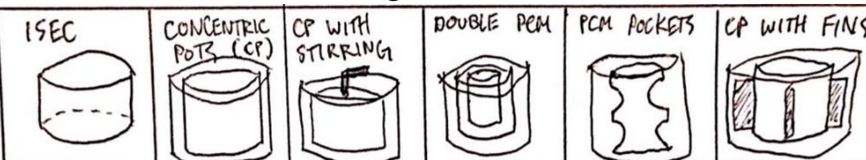
Pugh Matrix

Function: Conductance



Criteria \ Concepts	ISEC	Concentric Pots (CP)	CP with stirring PCM	Double PCM (3 pots)	Pockets with increased PCM	Fins in PCM
Cost	S	–	–	–	–	–
Max Internal Temp	S	+	+	+	+	+
Max External Temp	S	+	+	+	–	–
Time to Reach PC	S	+	+	+	–	+
Assembly Simplicity	S	S	S	S	–	–
Safety	S	S	–	S	–	S
Cook Time	S	+	+	+	+	+

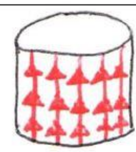
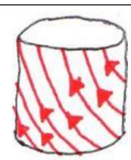
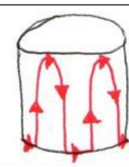
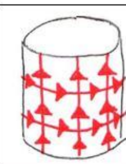
Function: Pot Configuration



CRITERIA \ CONCEPTS	ISEC	CONCENTRIC POTS (CP)	CP WITH STIRRING	DOUBLE PCM	PCM POCKETS	CP WITH FINS
COST	S	–	–	–	–	–
COOK VOLUME	S	S	S	S	S	S
SIZE	S	–	–	–	–	–
SAFETY	S	+	+	+	+	+
MANUFACTURING COMPLEXITY	S	–	–	–	–	–

Function: Insulation

CONCEPTS / CRITERIA	RICE HULLS	FIBERGLASS	UNDERGROUND	CONCRETE	FABRIC	MUD	AIR GAP	FOAM	CERAMIC	SAND
THERMAL CONDUCTIVITY	S	+	+	S	+	−	+	+	+	−
THERMAL CAPACITY	S	+	+	+	−	+	+	S	+	+
IGNITION TEMPERATURE	S	+	+	+	−	+	+	+	+	+
COST	S	−	S	−	−	S	−	−	−	S
ASSEMBLY SIMPLICITY	S	S	−	S	S	S	S	S	−	S
FOOD SAFETY	S	−	S	−	S	S	+	S	−	S
DENSITY	S	+	+	−	S	−	+	+	−	−
EASE OF ACCESS	S	−	+	−	−	S	+	−	−	S

Function	Diode Configuration					
Concepts						
Criteria	Bottom edge of the pot	Vertical lines	Spiral lines	Crown	Hoops	Grid
Number of Diodes	S	-	-	-	-	-
Circuit Simplicity	S	-	-	S	S	-
Assembly Simplicity	S	-	-	-	S	-
Even Heating	S	+	+	+	+	+
Ease of Isolation from PCM	S	S	-	-	S	-

Weighted Decision Matrix

ISEC with thermal storage		Legend:			
		pot configuration,PCM, added conduction,diode configuration,insulation,PV panel			
	Ideas	CP, erythritol,N/A, hoop, fiberglass,100W		CP, erythritol, hoop, fins, fiberglass,100W	
Functions	Weight	Score	Weighted Score	Score	Weighted Score
Cost	8	6	48	5	40
Safety	4	9	36	9	36
Durability	3	9	27	9	27
Cooking power	8	4	32	6	48
Cooking capacity	6	6	36	7	42
Ease of use	4	9	36	9	36
Manufacturability	4	8	32	6	24
		Total	247	Total	253

magnesium chloride hexahydrate		double PCM			
CP, mg cl, N/A,hoop, fiberglass,100W		dPCM, erythritol/d-mannitol, N/A,hoop, fiberglass,100W		dPCM, mg cl/d-mannitol, N/A,hoop, fiberglass,100W	

Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
7	56	3	24	4	32
8	32	8	32	7	28
6	18	7	21	5	15
6	48	7	56	8	64
4	24	6	36	5	30
9	36	8	32	8	32
8	32	5	20	5	20
Total	246	Total	221	Total	221

CP, erythritol, fins,crown, fiberglass,100 W		CP, erythritol, N/A,hoop,air gap,100W		CP, erythritol, N/A,hoop,rice husk,100W		CP, erythritol,N/A, hoop, fiberglass,200 W	
Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
5	40	7	56	7	56	2	16
9	36	8	32	6	24	7	28
9	27	9	27	7	21	9	27
6	48	3	24	4	32	6	48
7	42	5	30	6	36	10	60
9	36	9	36	9	36	9	36
4	16	10	40	9	36	8	32
Total	245	Total	245	Total	241	Total	247

We decided on the selection of concentric pots, erythritol, fins, diode hoop, and fiberglass insulation using a 100 W PV panel.

Winner with 253 Points

Appendix D: EES Lumped Capacitance Models

Lumped Capacitance Model for Erythritol

Notes

All units base SI unless otherwise noted

Part 1 - Full Model for Materials with Complete Thermophysical Properties

Outputs

m_{min} *= minimum required mass to bring 4L of water to a boil. Assumes 100 thermal efficiency and energy continues to transfer down to a PCM temp of 100 C*

m_{max} *= maximum amount of mass that could be fully melted after 8 hours of constant power*

m_{design} *= weighted average of* m_{min} *and* m_{max}

V_{PCM} *= volume of PCM. Note, this is maximum volume (i.e. accounts for thermal expansion from solid to liquid)*

s_{design} *= required spacing between concentric cylindrical pots to get* V_{design}

Inner Pot Geometry

$$V_{in,i} = 0.005$$

$$h_{in,i} = 0.6 \cdot d_{in,i}$$

$$V_{in,i} = \pi \cdot \left[\frac{d_{in,i}}{2}\right]^2 \cdot h_{in,i}$$

$$t_w = \frac{1}{32} \cdot 0.0254$$

$$t_b = \frac{1}{32} \cdot 0.0254$$

$$h_{in,o} = h_{in,i} + t_b$$

$$d_{in,o} = d_{in,i} + 2 \cdot t_w$$

$$V_{in,o} = \pi \cdot \left[\frac{d_{in,o}}{2}\right]^2 \cdot h_{in,o}$$

Outer Pot Geometry

$$V_{design} = V_{PCM} \cdot (1 + SF_V)$$

$$SF_V = 0.1$$

$$V_{design} = \pi \cdot \left[\frac{d_o}{2}\right]^2 \cdot h_o - V_{in,o}$$

$$d_o = d_{in,o} + 2 \cdot s_{design}$$

$$h_o = h_{in,o} + s_{design}$$

Thermal Properties of Erythritol

$T_m = 118$

$h_m = 330 \cdot 1000$

$c_s = 1.38 \cdot 1000$

$c_l = 2.76 \cdot 1000$

$\rho_l = \frac{1.3}{1000} \cdot 100^3$

Propeties Water and Environment

$T_h = 150$

$T_{H2O} = 100$

$T_{amb} = 30$

$c_{H2O} = 4184$

$V_{H2O} = 0.004$

$\rho_{H2O} = 1000$

$m_{H2O} = V_{H2O} \cdot \rho_{H2O}$

Energy

$P_{net} = 100$

$E_{minH2O} = m_{H2O} \cdot c_{H2O} \cdot (T_{H2O} - T_{amb})$

$E_{min} = E_{minH2O} + E_{sub100}$

$E_{sub100} = m_{min} \cdot c_s \cdot (T_{H2O} - T_{amb})$

$E_{min} = m_{min} \cdot (c_s \cdot (T_m - T_{amb}) + c_l \cdot (T_h - T_m) + h_m)$

$E_{max} = m_{max} \cdot (c_s \cdot (T_m - T_{amb}) + h_m)$

$E_{max} = P_{net} \cdot 3600 \cdot 8$

Volume

$m_{design} = m_{min} \cdot (1 - DF_V) + m_{max} \cdot DF_V$

$DF_V = 0.5$

$V_{PCM} = \frac{m_{design}}{\rho_l}$

$V_{out} = V_{design} + V_{in,o}$

Cost

$Costpermass_{proto} = 7.3$

$Costpermass_{bulk} = 1$

$Cost_{proto} = m_{design} \cdot Costpermass_{proto}$

$Cost_{bulk} = m_{design} \cdot Costpermass_{bulk}$

SOLUTION

Unit Settings: SI C Pa J mass deg

$Costpermass_{bulk} = 1$	$Costpermass_{proto} = 7.3$	$Cost_{bulk} = 4.512$
$Cost_{proto} = 32.93$	$c_{H2O} = 4184$	$c_l = 2760$
$c_s = 1380$	$DF_V = 0.5$	$d_{in,i} = 0.2197$
$d_{in,o} = 0.2213$	$d_o = 0.2693$	$E_{max} = 2.880E+06$
$E_{min} = 1.427E+06$	$E_{minH2O} = 1.172E+06$	$E_{sub100} = 255368$
$h_{in,i} = 0.1318$	$h_{in,o} = 0.1326$	$h_m = 330000$
$h_o = 0.1566$	$m_{design} = 4.512$	$m_{H2O} = 4$
$m_{max} = 6.38$	$m_{min} = 2.644$	$P_{net} = 100$
$\rho_{H2O} = 1000$	$\rho_l = 1300$	$SF_V = 0.1$
$s_{design} = 0.02398$	$T_{amb} = 30$	$t_b = 0.0007938$
$T_h = 150$	$T_{H2O} = 100$	$T_m = 118$
$t_w = 0.0007938$	$V_{design} = 0.003817$	$V_{H2O} = 0.004$
$V_{in,i} = 0.005$	$V_{in,o} = 0.005103$	$V_{out} = 0.008921$
$V_{PCM} = 0.00347$		

No unit problems were detected.

Lumped Capacitance Model for MgCl2-6H2O

Notes

All units base SI unless otherwise noted

Part 1 - Full Model for Materials with Complete Thermophysical Properties

Outputs

m_{min} = minimum required mass to bring 4L of water to a boil. Assumes 100 thermal efficiency and energy continues to transfer down to a PCM temp of 100 C

m_{max} = maximum amount of mass that could be fully melted after 8 hours of constant power

m_{design} = weighted average of m_{min} and m_{max}

V_{PCM} = volume of PCM. Note, this is maximum volume (i.e. accounts for thermal expansion from solid to liquid)

s_{design} = required spacing between concentric cylindrical pots to get V_{design}

Inner Pot Geometry

$$V_{in,i} = 0.005$$

$$h_{in,i} = 0.6 \cdot d_{in,i}$$

$$V_{in,i} = \pi \cdot \left[\frac{d_{in,i}}{2}\right]^2 \cdot h_{in,i}$$

$$t_w = 1 / 8 \cdot 0.0254$$

$$t_b = 1 / 8 \cdot 0.0254$$

$$h_{in,o} = h_{in,i} + t_b$$

$$d_{in,o} = d_{in,i} + 2 \cdot t_w$$

$$V_{in,o} = \pi \cdot \left[\frac{d_{in,o}}{2}\right]^2 \cdot h_{in,o}$$

Outer Pot Geometry

$$V_{design} = V_{PCM} \cdot (1 + SF_V)$$

$$SF_V = 0.15$$

$$V_{design} = \pi \cdot \left[\frac{d_o}{2}\right]^2 \cdot h_o - V_{in,o}$$

$$d_o = d_{in,o} + 2 \cdot s_{design}$$

$$h_o = h_{in,o} + s_{design}$$

Thermal Properties of MgCl-6H2O

$T_m = 114$

$h_m = 167 \cdot 1000$

$c_s = 2.2 \cdot 1000$

$c_l = 2.6 \cdot 1000$

$\rho_l = \frac{1.45}{1000} \cdot 100^3$

Propeties Water and Environment

$T_h = 150$

$T_{H2O} = 100$

$T_{amb} = 30$

$c_{H2O} = 4184$

$V_{H2O} = 0.004$

$\rho_{H2O} = 1000$

$m_{H2O} = V_{H2O} \cdot \rho_{H2O}$

Energy

$P_{net} = 100$

$E_{minH2O} = m_{H2O} \cdot c_{H2O} \cdot (T_{H2O} - T_{amb})$

$E_{min} = E_{minH2O} + E_{sub100}$

$E_{sub100} = m_{min} \cdot c_s \cdot (T_{H2O} - T_{amb})$

$E_{min} = m_{min} \cdot (c_s \cdot (T_m - T_{amb}) + c_l \cdot (T_h - T_m) + h_m)$

$E_{max} = m_{max} \cdot (c_s \cdot (T_m - T_{amb}) + h_m)$

$E_{max} = P_{net} \cdot 3600 \cdot 8$

Volume

$m_{design} = m_{min} \cdot (1 - DF_V) + m_{max} \cdot DF_V$

$DF_V = 0.5$

$V_{PCM} = \frac{m_{design}}{\rho_l}$

Cost

$Costpermass_{proto} = 7$

$Costpermass_{bulk} = 0.3$

$Cost_{proto} = m_{design} \cdot Costpermass_{proto}$

$Cost_{bulk} = m_{design} \cdot Costpermass_{bulk}$

SOLUTION

Unit Settings: SI C Pa J mass deg

$Costpermass_{bulk} = 0.3$	$Costpermass_{proto} = 7$	$Cost_{bulk} = 1.831$
$Cost_{proto} = 42.72$	$c_{H2O} = 4184$	$c_l = 2600$
$c_s = 2200$	$DF_V = 0.5$	$d_{in,i} = 0.2197$
$d_{in,o} = 0.2261$	$d_o = 0.2828$	$E_{max} = 2.880E+06$
$E_{min} = 1.791E+06$	$E_{minH2O} = 1.172E+06$	$E_{sub100} = 619129$
$h_{in,i} = 0.1318$	$h_{in,o} = 0.135$	$h_m = 167000$
$h_o = 0.1634$	$m_{design} = 6.103$	$m_{H2O} = 4$
$m_{max} = 8.186$	$m_{min} = 4.02$	$P_{net} = 100$
$\rho_{H2O} = 1000$	$\rho_l = 1450$	$SF_V = 0.15$
$s_{design} = 0.02835$	$T_{amb} = 30$	$t_b = 0.003175$
$T_h = 150$	$T_{H2O} = 100$	$T_m = 114$
$t_w = 0.003175$	$V_{design} = 0.004841$	$V_{H2O} = 0.004$
$V_{in,i} = 0.005$	$V_{in,o} = 0.005421$	$V_{PCM} = 0.004209$

No unit problems were detected.

Appendix E: Insulation Comparison

Parameter	**Units**	**Rice Hulls**	**Fiberglass**	**Perlite**
Cost	$/m^3	0	60	45
Thermal Conductivity	W/m-K	0.12	0.039	0.065
Ignition Temperature	Celsius	<400	1121	900
Density	kg/m^3	80 – 120	0.5 - 1	30 – 150

Appendix F: MATLAB Conduction Model

The team's preliminary testing included the creation of a 2D conduction model of the cooker and PCM assembly. Analysis was completed to verify the diode chain heating element's ability to melt the PCM. The full Matlab program is shown below.

```
% 2D Thermal Conduction Model for ISEC W/ TS
 % Matthew Weeman, Marcus Strutz, Justin Unger, Nate Christler
 % ME 428 - 05
 % Prof. Rossman
 % 11/06/2018

format short;
 format compact;
 close all;
 clearvars;
 clc;
```

Configuration Dimensions

```
twallin = 1/8;          %[in] Small pot wall thickness
 twallout = twallin;     %[in] Big pot wall thickness, assume same
 tbasein = 1/4;          %[in] Small pot base thickness
 tbaseout = tbasein;     %[in] Big pot base thickness, assume same
 dinin = 8;              %[in] ID of the internal pot
 dinout = 10;            %[in] ID of the outer pot
 hin = 8;                %[in] External height of the small pot
 hout = 10;              %[in] External height of the big pot
 ddiode = 1/16;          %[in] Diode diameter
 ldiode = 1/8;           %[in] Diode length

 tcavw = (dinout-(dinin+(2*twallin)))/2; %[in] Gap thick. b/w pot walls
 tcavb = (hout-hin);              %[in] Gap thick b/w pot bases
 Lcavo = hout-tbaseout;           %[in] Length of cavity outer side
 IDcav = dinin+(2*twallin);       %[in] ID of cavity
```

Thermal Properties

```
kpotin = 118;  %[BTU/hr-ft-F] Therm. cond. of inner pot, assume aluminum
 kpotin = kpotin*1.37; %[W/mK] Unit conversion
 kpotout = kpotin;     %[BTU/hr-ft-F] Therm. cond. of outer pot, assume same
 kesol = 2.64;         %[W/mK] Therm. cond. of solid erythritol
 Tdiode = 150;         %[C] Steady state temp. of diodes
 Tosurf = 80;          %[C] Steady state temp. of outside pot
 Tisurf = 50;          %[C] Steady state temp. of inner surface
```

Nodal Network

```
grid = 1/16;                    %[in] Gridspacing
 Ny = hout/grid;                %[-] Total rows in model
 Nx = (dinout+(2*twallout))/grid;  %[-] Total Columns in model
 twi = twallin/grid;            %[-] Small pot wall thick. to nodes
 two = twallout/grid;           %[-] Big pot wall thick. to nodes
 dbi = tbasein/grid;            %[-] Small pot base thick. to nodes
 dbo = tbaseout/grid;           %[-] Big pot base thick. to nodes
 g = tcavw/grid;                %[-] Wall gap to nodes
 b = tcavb/grid;                %[-] Base gap to nodes
 d = 1/grid;                    %[-] Diode dist. from bottom of small pot
 dd = ddiode/grid;              %[-] Diode diam to nodes
```

Formula Matrix

```
form = (ones(Ny,Nx)).*100;     %Create zero matrix of model size


form(:,1) = 0;      %Pop. big pot left outer wall  w no formula
 form(:,Nx)= 0;      %Pop. big pot right outer wall w no formula
 form(Ny,:) = 0;     %Pop. big pot outer bottom wall w no formula

form([Ny-1:-1:(Ny-dbo+1)],2:Nx-1) = 1;       %Pop. big pot bottom w form 1
 form([1:1:(Ny-1)],[2:1:two]) = 1;           %Pop. big pot left w form 1
 form([1:1:(Ny-1)],[Nx-1:-1:(Nx-two+1)]) = 1; %Pop. big pot right w form 1

form([1:1:Ny-dbo+1],two) = 2;         %Pop. big pot left inner w form 2
 form([1:1:Ny-dbo+1],(Nx-two+1)) = 3;   %Pop. big pot right inner w form 3
 form((Ny-dbo+1),[two:1:Nx-two+1]) = 4; %Pop. big pot bottom inner w form 4
 form(Ny-dbo+1,two) = 5;           %Pop. big pot inner left corn. w form 5
 form(Ny-dbo+1,Nx-two+1) = 6;      %Pop. big pot inner right corn. w form 6

form([1:1:Ny-dbo],[two+1:1:two+g]) = 1;          %Pop. left gap w form 1
 form([1:1:Ny-dbo],[(Nx-two):-1:(Nx-two+1-g)]) = 1;%Pop. right gap w form 1
 form([Ny-dbo:-1:Ny-dbo-b+1],[two+1:1:Nx-two-1])=1;%Pop. bottom gap w form 1

%Pop. inner pot left outer wall w form 7
 form([1:1:Ny-dbo-b],two+g+1) = 7;
 %Pop. inner pot right outer wall w form 8
 form([1:1:Ny-dbo-b],Nx-two-g) = 8;
 %Pop. inner pot outer bottom wall w form 9
 form(Ny-dbo-b,[(two+g+1):1:(Nx-two-g)]) = 9;
 %Pop. inner pot outer left corner w form 10
 form(Ny-dbo-b,two+g+1) = 10;
```

```
%Pop. inner pot outer right corner w form 11
form(Ny-dbo-b,Nx-two-g) = 11;

%Pop. small pot left w form 1
form([1:1:Ny-dbo-b-1],[two+g+2:1:two+g+twi]) = 1;
%Pop. small pot right w form 1
form([1:1:Ny-dbo-b-1],[Nx-two-g-1:-1:Nx-two-g-twi+1]) = 1;
%Pop. small pot bottom w form 1
form([Ny-dbo-b-1:-1:Ny-dbo-b+1-dbi],[two+g+1+twi:1:Nx-two-g-twi+1]) = 1;

%Pop. small pot inner left w no form
form([1:1:Ny-dbo-b+1-dbi],two+g+twi) = 0;
%Pop. small pot inner right w no form
form([1:1:Ny-dbo-b+1-dbi],Nx-two-g-twi+1) = 0;
%Pop. small pot bottom w no form
form(Ny-dbo-b+1-dbi,[two+g+twi:1:Nx-two-g-twi+1]) = 0;

%Pop. left diode w no form.
form([Ny-dbo-b-d:-1:Ny-dbo-b-d-dd+1],[two+g-1:-1:two+g-dd]) = 0;
%Pop. right diode w no form.
form([Ny-dbo-b-d:-1:Ny-dbo-b-d-dd+1],[Nx-two-g+2:1:Nx-two-g+dd+1]) = 0;
%Pop. left top w no form
form(1,[1:1:two+g+twi]) = 0;
%Pop. right top w no form
form(1,[Nx-two-g-twi+1:1:Nx]) = 0;
```

Physical Model

```
model = (ones(Ny,Nx)).*25; %Create model & fill with amb. temp.

%Pop. big pot outer surfaces with Tosurf
model(:,1) = Tosurf;
model(:,Nx)= Tosurf;
model(Ny,:) = Tosurf;
model(1,[1:1:two+g+twi]) = Tosurf;
model(1,[Nx-two-g-twi+1:1:Nx]) = Tosurf;

%Pop. small pot inner surfaces with Tisurf
model([1:1:Ny-dbo-b+1-dbi],two+g+twi) = Tisurf;
model([1:1:Ny-dbo-b+1-dbi],Nx-two-g-twi+1) = Tisurf;
model(Ny-dbo-b+1-dbi,[two+g+twi:1:Nx-two-g-twi+1]) = Tisurf;

%Pop. diodes with Tdiode
model([Ny-dbo-b-d:-1:Ny-dbo-b-d-dd+1],...
    [two+g-1:-1:two+g-dd]) = Tdiode;
```

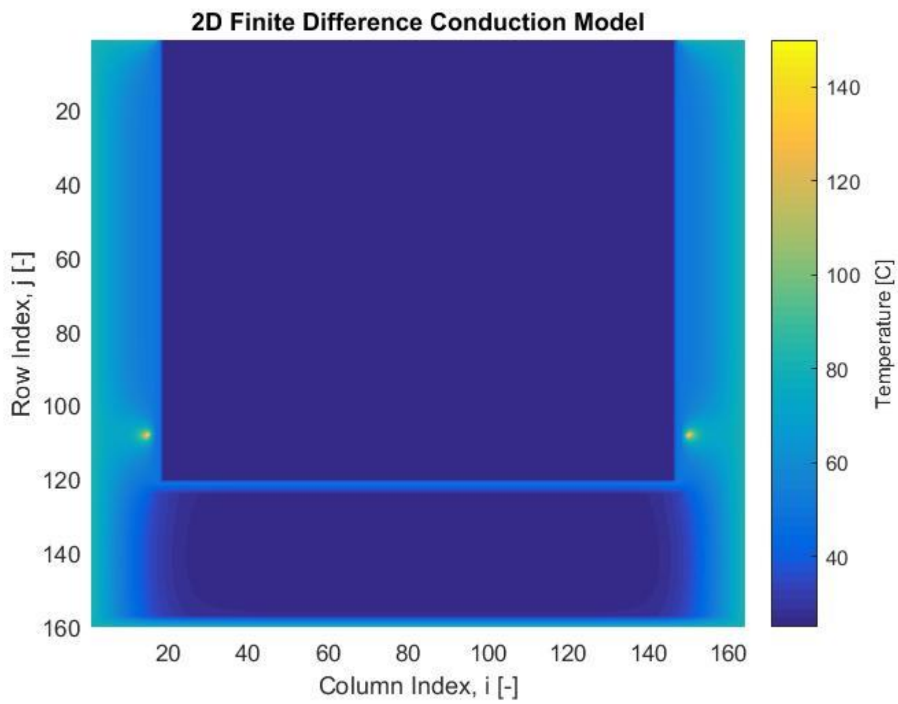
```
model([Ny-dbo-b-d:-1:Ny-dbo-b-d-dd+1],...
    [Nx-two-g+2:1:Nx-two-g+dd+1]) = Tdiode;
```

Finite Difference Equations

```
for n = 1:100
    % For each column, go row by row and based on that node's corresponding
    % designation in the "form" matrix apply the correct finite difference
    % formula to that node in the "model" matrix. Repeat this 100 times.
  for i = 1:Nx
      for j = 1:Ny
          F = form(j,i);
          % formula1 = internal node
          % formula2 = bi-material vertical surface
          % formula3 = bi-material horizontal surface
          % formula4 = bi-material bottom left corner
          % formula5 = bi-material bottom right corner
          if F >= 1 && F < 2
              model(j,i) = formula1(model,j,i);
          elseif F >= 2 && F < 3
              model(j,i) = formula2(kpotin,kesol,model,j,i);
          elseif F >= 3 && F < 4
              model(j,i) = formula2(kesol,kpotin,model,j,i);
          elseif F >= 4 && F < 5
              model(j,i) = formula3(kesol,kpotin,model,j,i);
          elseif F >= 5 && F < 6
              model(j,i) = formula4(kpotin,kesol,model,j,i);
          elseif F >= 6 && F < 7
              model(j,i) = formula5(kpotin,kesol,model,j,i);
          elseif F >= 7 && F < 8
              model(j,i) = formula2(kesol,kpotin,model,j,i);
          elseif F >= 8 && F < 9
              model(j,i) = formula2(kpotin,kesol,model,j,i);
          elseif F >= 9 && F < 10
              model(j,i) = formula3(kpotin,kesol,model,j,i);
          elseif F >= 10 && F < 11
              model(j,i) = formula4(kesol,kpotin,model,j,i);
          elseif F >= 11 && F <12
              model(j,i) = formula5(kesol,kpotin,model,j,i);
          else
          end
      end
  end
end
```

Plot

```
[M,N] = size(model);
 figure(1)
 h1 = axes;
 pcolor(1:N,1:M,model);
 set(h1,'Ydir','reverse'); %Flip Figure Axis to Match FDM Orientation
 shading('interp'); % Color Gradient
 title('2D Finite Difference Conduction Model');
 xlabel('Column Index, i [-]');
 ylabel('Row Index, j [-]');
 c = colorbar;
 c.Label.String = 'Temperature [C]';
```



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Appendix G: MATLAB Component Efficiencies

```
% PCM Thermal Efficiency
% ME 428-5
% InSECTS
clear;
clc;
```

Erythritol thermal properties (e)

```
hf_e=347;
Tm_e=118;
cs_e=1.4;
cl_e=2.8;
```

MgCl2-6H2O thermal properties (m)

```
hf_m=167;
Tm_m=117;
cs_m=2.2;
cl_m=2.6;
```

test parameters

```
Tamb=30;
Tf=[120:1:200];
```

PCM Efficiency

```
esub100_e=cs_e*(100-Tamb);
esolid_e=cs_e*(Tm_e-100);
eliquid_e=cl_e*(Tf-Tm_e);
efus_e=hf_e;
etotal_e=esolid_e+esub100_e+eliquid_e+efus_e;
euseful_e=etotal_e-esub100_e;
eta_e=euseful_e./etotal_e;

esub100_m=cs_m*(100-Tamb);
esolid_m=cs_m*(Tm_m-100);
eliquid_m=cl_m*(Tf-Tm_m);
efus_m=hf_m;
etotal_m=esolid_m+esub100_m+eliquid_m+efus_m;
euseful_m=etotal_m-esub100_m;
eta_m=euseful_m./etotal_m;
figure;
plot(Tf,eta_e,Tf,eta_m);
legend('Erythritol','MgCl2-6H2O','location','northwest');
ylabel('PCM Efficiency');
```

```
xlabel('Temperature (Degrees C)')
grid on;
```

Insulation Efficiency 2

```
R_ratio=20;         % The ratio of the net heat transfer resistance of the
                    % path out of the system through the insulation
                    % to the net heat transfer resistance into the water
Trange=[100:1:200];
deltaT_o=Trange-Tamb;
deltaT_i=Trange-100;
q_o=deltaT_o./(R_ratio);
q_i=deltaT_i./1;
q_total=q_o+q_i;
eta_ins=q_i./q_total;

Tinterest=[110,117.5,150];
deltaT2_o=Tinterest-Tamb;
deltaT2_i=Tinterest-100;
q2_o=deltaT2_o./(R_ratio);
q2_i=deltaT2_i./1;
q2_total=q2_o+q2_i;
eta2_ins=q2_i./q2_total;

figure;
hold on;
plot(Trange,eta_ins);
scatter(Tinterest,eta2_ins);
hold off
ylabel('Insulation Efficiency 2');
xlabel('Temperature (Degrees C)')
grid on;

figure;
hold on;
plot(Trange,eta_ins);
scatter(Tinterest,eta2_ins);
hold off
ylabel('Insulation Efficiency 2');
xlabel('Temperature (Degrees C)')
ylim([.65,1]);
grid on;
```

Insulation Efficiency 1 & Cooking Power

```
Trange3=[30:.5:175];
hloss=[0:.5:145];
locate=Trange3==117.5;
indiceloc=find(locate);
hloss_scale=hloss./hloss(indiceloc);

Trange4=[100:.5:175];
```

```
cookpower=[0:.5:75];
locate2=Trange4==117.5;
indiceloc2=find(locate2);
cookpower_scale=cookpower./cookpower(locate2);

figure;
hold on;
xlabel('Temperature (Degrees C)');
ylabel('Normalized Heat')
plot(Trange3,hloss_scale,'r');
plot(Trange4, cookpower_scale,'b');
xlim([30,175]);
grid on;
legend('Normalized Heat Loss','Normalized Cooking Power','location','northwest')
```

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Appendix H: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: ISEC with Phase Change, Team 55 Advisor: Rossman Date: 2/7/2019

Y	N	
☐	☒	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	☒	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☐	☒	3. Will any part of the design undergo high accelerations/decelerations?
☐	☒	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	☒	5. Could the system produce a projectile?
☐	☒	6. Could the system fall (due to gravity), creating injury?
☐	☒	7. Will a user be exposed to overhanging weights as part of the design?
☐	☒	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	☒	9. Will any part of the electrical systems not be grounded?
☐	☒	10. Will there be any large batteries (over 30 V)?
☐	☒	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	☒	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	☒	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	☒	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☒	☐	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	☒	16. Could the system generate high levels (>90 dBA) of noise?
☐	☒	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☒	☐	18. Is it possible for the system to be used in an unsafe manner?
☒	☐	19. For powered systems, is there an emergency stop button?
☐	☒	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
15 Fiberglass insulation can be irritable to skin and eyes	Wear personal protective equipment while installing insulation and ensure insulation is isolated from cooking pot	11/14/18	2/14
18 Cooker can potentially start a fire if operated outside of insulation	wire cooker leads through the insulation so the cooker must be surrounded by it	1/29/19	
19 Diodes can overheat	If we implement bi-metallic switches in the diode circuit we can interrupt current flow and prevent overheating	11/14/18	

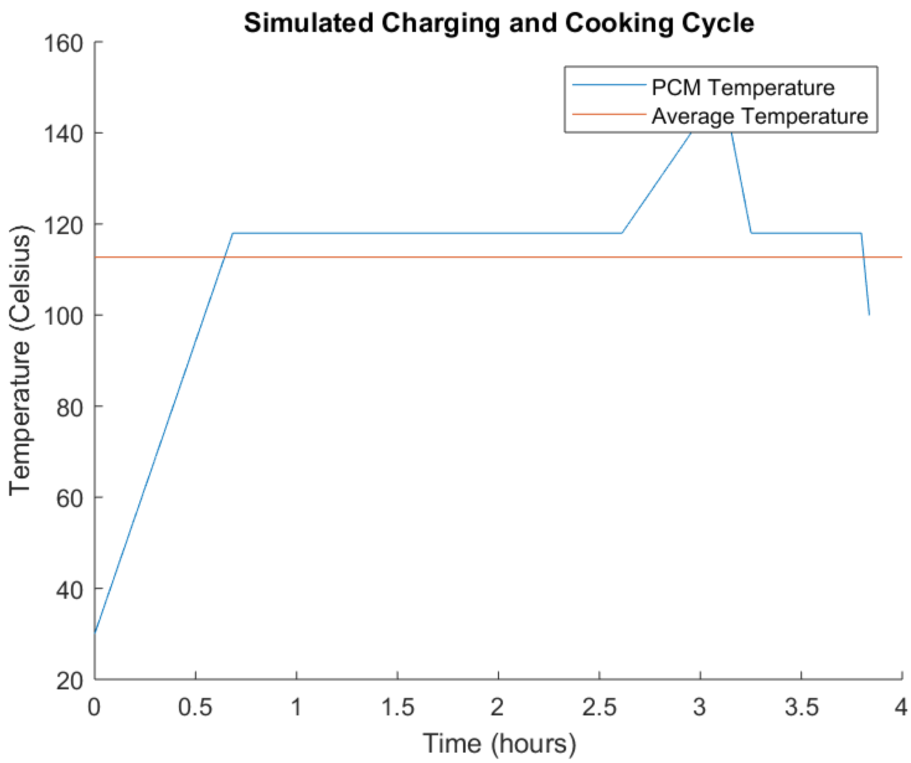
Appendix I: MATLAB Thermal Efficiency and Cooking Power

```
% Thermal Efficiency and Cooking Power calculations
% ME 428-5
% InSECTS
clear;
clc;
```

Part 1 - Simulating a Full Thermal Cycle for Temperature

```
P_charge_ideal=100;          % Nominal Power of Solar Panel
P_charge=85;                 % Expected power delivered to PCM (charging)
P_drain=300;                 % Expected power drained from PCM (cooking)
T_min=30;                    % lowest temp of PCM
T_max=150;                   % highest temp of PCM
T_boil=100;                  % temp of boiling water
Tamb=30;                     % ambient air temp

% Here I call a function to calculate the temperature and time at each second
Time_Temp_c=TempvTime(T_min,T_max,P_charge);
time_c=Time_Temp_c{1};                          % time vector
Temp_c=Time_Temp_c{2};                          % temp vector

% figure;                                       % plot charging T v t plot
% plot(time_c,Temp_c);
% T_charge=mean(Temp_c)

% Run function for cooking portion of cycle
Time_Temp_d=TempvTime(T_max,T_boil,-P_drain);
time_d=Time_Temp_d{1};
Temp_d=Time_Temp_d{2};

% figure;                       % plot cooking T v t plot
% plot(time_d,Temp_d);
% T_cook=mean(Temp_d)


time_charge=max(time_c);            % here I combine charging and cooking
time_t=[time_c,time_charge+time_d]; % data
Temp_t=[Temp_c,Temp_d];
time_t_hour=time_t/3600;
E_charge=P_charge_ideal*time_charge;

T_ave=mean(Temp_t);                 % plot full cycle
t_max=max(time_t_hour);
figure;
hold on;
plot(time_t_hour,Temp_t);
xlabel('Time (hours)');
ylabel('Temperature (Celsius)');
title('Simulated Charging and Cooking Cycle');
plot([0,4],[T_ave,T_ave]);
```

```
hold off;
legend('PCM Temperature','Average Temperature');
```



Part 2 - Estimating insulation efficiency

```
L=1.15*2.54/100;              % minimum fiberglass thickness
d_in=11.1;                    % OD outer pot (inches)
h_in=5;                       % height outer pot (inches)
d_m=d_in*2.54/100;            % OD (m)
h_m=h_in*2.54/100;            % h (m)
A=pi*d_m*h_m+2*1/4*pi*d_m^2;  % heat transfer area
k=.04;                        % thermal conductivity of fiberglass
R=L/(k*A);                    % thermal resistance
P_hl=(T_ave-Tamb)/R;          % heat loss
eff_hlc=(100-P_hl)/100        % insulation efficiency
```

```
eff_hlc =

    0.7311
```

Part 3A - estimating cook speed (conduction)

```
clear;
m=1700;     % grams
Tamb=30;    % C
```

```
Tmax=150;   % C

hf=347;     % J/g-C
Tm=118;     % C
cs=1.4;     % J/g-C
cl=2.8;     % J/g-C

E_solid=cs*m*(Tm-Tamb);
E_melt=hf*m;
E_liq=cl*m*(Tm-Tamb);

E1=E_solid;
E2=E_solid+E_melt;
E3=E_solid+E_melt+E_liq;
t=1;
Tw=30;
Ew=0;
Ee=E3;
Te=150;
A=(4*pi*4.5+2^2*pi)*2.54^2/100^2;
k=.5295;        % mean of k_liq and k_sol for erythritol
L=1*2.54/100;   % max thickness of erythritol (conservative)
R=L/(k*A);      % estimated conduction thermal resistance
mw=1000;
cw=4.18;
    while Tw<=100
        q=(Te-Tw)/R;
        Ee=Ee-q;
        Ew=Ew+q;
        Tw=Tamb+Ew/(mw*cw);
        if Ee>E2
            Te=Tm+(Ee-E2)/(m*cl);
        elseif Ee>=E1
            Te=Tm;
        else
            Te=Tamb+Ee/(m*cs);
        end
        q_vect(t)=q;
        t_vect(t)=t;
        T_water(t)=Tw;
        T_eryth(t)=Te;
        delta_T(t)=Te-Tw;
        t=t+1;
    end
display(t/60)
```

```
54.8667
```

Part 3B - Estimating Cook Speed (convection)

```
    m=1700;      % mass of PCM (g)
    Tamb=30;     % C
    Tmax=150;    % C

    hf=347;      % J/g-C
    Tm=118;      % C
    cs=1.4;      % J/g-C
    cl=2.8;      % J/g-C

    E_solid=cs*m*(Tm-Tamb);      % Energy stored in heating solid
    E_melt=hf*m;                 % Energy stored in PC
    E_liq=cl*m*(Tm-Tamb);        % energy stored in heating liquid

    E1=E_solid;                  % net energy at beginning of PC
    E2=E_solid+E_melt;           % net energy at end of PC
    E3=E_solid+E_melt+E_liq;     % Net energy at full charge
    t2=1;                        % time (s)
    Tw=30;                       % initial water temp
    Ew=0;                        % initial water energy
    Ee=E3;                       % initial PCM energy
    Te=150;                      % initial PCM temp
    A=(4*pi*4.5+2^2*pi)*2.54^2/100^2;   %heat transfer Area
    h=100;                       % conv coeff
    Rc=1/(h*A);                  % thermal resistance conv
    mw=1000;                     % mass water
    cw=4.18;                     % specific heat water
    while Tw<=100
        q=(Te-Tw)/Rc;            % heat in 1 sec
        Ee=Ee-q;                 % subtract heat from PCM
        Ew=Ew+q;                 % add heat to Water
        Tw=Tamb+Ew/(mw*cw);      % temp of water
        if Ee>E2                     % if loop calculates PCM temp
            Te=Tm+(Ee-E2)/(m*cl);
        elseif Ee>=E1
            Te=Tm;
        else
            Te=Tamb+Ee/(m*cs);
        end
        q_vect(t2)=q;            % vector of heat(t)
        t_vect(t2)=t2;           % vector of time
        T_water(t2)=Tw;          % vector of T_water(t)
        T_eryth(t2)=Te;          % vector of T_PCM(t)
        delta_T(t2)=Te-Tw;       % vector of delta_T(t)
        t2=t2+1;
    end
display(t2/60)                   % disp time in minutes
```

```
11.4500
```

Time_Temp function file

```
function [ Time_Temp ] = TempvTime( Ti,Tf,P )
```

```
% TempvTime takes init and final temp of PCM and power rate and calculates
% the temperature of PCM as a function of time
```

Thermal Properties

```
    m=1700;     % grams
    Tamb=30;    % C
    Tmax=150;   % C

    hf=347;     % J/g-C
    Tm=118;     % C
    cs=1.4;     % J/g-C
    cl=2.8;     % J/g-C

    E_solid=cs*m*(Tm-Tamb);
    E_melt=hf*m;
    E_liq=cl*m*(Tm-Tamb);

    E1=E_solid;
    E2=E_solid+E_melt;
    E3=E_solid+E_melt+E_liq;

    if Ti<118
        E_i=m*cs*(Ti-Tamb);
    else
        E_i=E2+m*cl*(Ti-Tm);
    end

    if Tf<118
        E_f=m*cs*(Tf-Tamb);
    else
        E_f=E2+m*cl*(Tf-Tm);
    end

    tmax_dec=(E_f-E_i)/P;
    tmax=round(tmax_dec);
    t_vect=[1:1:tmax];
    E_vect=E_i+P*t_vect;
    t=1;
while t<=tmax
    if E_vect(t)<E1
        T_vect(t)=Tamb+E_vect(t)/(m*cs);
    elseif E_vect(t)<=E2
        T_vect(t)=Tm;
    else
        T_vect(t)=Tm+(E_vect(t)-E2)/(m*cl);
    end
t=t+1;
end
```

```
Time_Temp={t_vect,T_vect};
```

```
Not enough input arguments.

Error in TempvTime (line 22)
    if Ti<118
```

```
end
```

Appendix J: EES – Design Mass and Cooking Capacity

$t_{hour} = 3$

$P_{nom} = 100$

$\eta_{ins} = 0.73$

$\eta_{sys} = 0.4$

$P_{charge} = \eta_{ins} \cdot P_{nom}$

$P_{net} = \eta_{sys} \cdot P_{nom}$

$T_m = 118$

$h_m = 330 \cdot 1000$ *J/kg*

$c_s = 1.38 \cdot 1000$ *J/kg-C*

$c_l = 2.76 \cdot 1000$ *J/kg-C*

$T_{amb} = 30$ *C*

$T_h = 150$ *C*

$E_{Charge} = E_s + E_m + E_l$ *J*

$E_s = m_{PCM} \cdot c_s \cdot (T_m - T_{amb})$ *J*

$E_l = m_{PCM} \cdot c_l \cdot (T_h - T_m)$ *J*

$E_m = m_{PCM} \cdot h_m$ *J*

$E_{Charge} = P_{charge} \cdot t_{charge}$ *J*

$t_{hour} = \dfrac{t_{charge}}{3600}$ *hr*

$T_{boil} = 100$ *C*

$\delta_{T,water} = T_{boil} - T_{amb}$ *C*

$E_{H20} = m_{H20} \cdot \delta_{T,water} \cdot c_{H20}$ *J*

$c_{H20} = 4.18 \cdot 1000$ *J/kg-C*

$E_{H20} = P_{net} \cdot t_{charge}$ *J*

$V_{H20} = 1 \cdot m_{H20}$ *L*

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$c_{H20} = 4180$	$c_l = 2760$	$c_s = 1380$
$\delta_{T,water} = 70$	$\eta_{ins} = 0.73$	$\eta_{sys} = 0.4$

E_{Charge} = 788400	E_{H20} = 432000	E_{l} = 129005
E_{m} = 482014	E_{s} = 177381	h_{m} = 330000
m_{H20} = 1.476	m_{PCM} = 1.461	P_{charge} = 73
P_{net} = 40	P_{nom} = 100	T_{amb} = 30
T_{boil} = 100	t_{charge} = 10800	T_{h} = 150
t_{hour} = 3	T_{m} = 118	V_{H20} = 1.476

No unit problems were detected.

Appendix K: FMEA

	System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN
2										
3	Insulation: prevent heat loss	Allows too much heat transfer	a) loss of energy b) food does not cook c) High external surface temperature	5	not using enough insulation	a) Preliminary Thermal Analysis b) Safety factor - adding more insulation that calculated	1	a) Temperature and heat transfer analysis while testing	1	5
4	Structural: support cooker assembly	cooker tips over	a) loss of food b) loss of PCM	4	impact or other force causes failure	a) Preliminary material selection analysis b) safe practice guidelines	2	a) Visual inspection of overall system after assembly	3	24
5	Structural: contain PCM	a) external pot ruptures b) internal pot ruptures c) flange does not completely seal	a) Food contaminated b) Total loss of PCM c) Decrease in insulation performance d) Decrease in PCM perfromance	8	a) cracks in pots b) significant impact on structural system c) poor flange manufacturing d) poor flange sealing techniques	a) Visual inspection of components prior to assembly b) Fit testing during assembly	6	a) Visual inspection of overall system after assembly	1	48
6	Structural: Contain Insulation	Outer pot ruptures	insulation is contaminated	8	Outside Force ie(human impact or dropping apparatus)	a) Preliminary material selection analysis b) safe practice guidelines c) Visual Inspection of components prior to assembly	1	a) Visual inspection of overall system after assembly	5	40
7		insulation housing ruptures	loss of energy	2	Outside Force ie(human impact or dropping apparatus)	a) Cautious action around device b) Strong Material	3	a) Visual inspection of overall system	4	24
8	Structural: contain food	inner pot breaks	a) food is lost b) food is contaminated	8	corrosion or fatigue of inner pot	a) Preliminary material selection analysis b) safe practice guidelines c) Visual Inspection of components prior to assembly	1	a) Visual inspection of overall system after assembly	4	32
9	Structural: seal PCM and food chambers (flange)	PCM leaks	a) PCM is lost b) food is contaminated c) insulation is contaminated	8	a) not creating a good seal b) poor manufacturing	a) Visual inspection of components prior to assembly b) Fit testing during assembly	6	a) Visual inspection of overall system after assembly	1	48
10		insulation contaminates PCM or food	a) insulation is lost b) food is contaminated	9	issues with outer pot or inner pot	a) Visual inspection of components prior to assembly b) Fit testing during assembly	1	a) Visual inspection of overall system after assembly	1	9

	System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken
2													
11	Thermal: assist conduction to and from PCM	Innadequate conduction / uneven melting	issues heating PCM	8	not enough conductance (lacking fins)	If necessary fins will be added	4	A) inspection of whether food was cooked	2	64	Multiple Conduction Tests prior to release to customers		
12		PCM doesn't melt	food does not cook	8	not enough heat to PCM	heating diodes longer	4	A) inspection of whether food was cooked	2	64	Multiple Conduction Tests prior to release to customers		
13	Thermal: Store Thermal Energy	PCM doesnt melt	food does not cook	6	improper heat transfer from diodes	Preliminary Thermal Analysis	6	A) inspection of whether food was cooked	2	72	Prior thermal testing to make sure PCM properly functions at current goals		
14		PCM solidifies too fast	food does not cook	6	too quick of a change in temperature	Open Chamber Testing	6	A) inspection of whether food was cooked	2	72	Prior thermal testing to make sure PCM properly functions at current goals		
15	Electronics: provide heat	Diodes do not get hot enough to melt PCM	no benefit from thermal storage	6	Diode connection is interrupted or power is compromised	Prototype Testing/ Preliminary Analysis	6	A) inspection of PCM during testing	2	72	Prior thermal testing to ensure diodes reach necessary temperature for proper function	1/29	Completed test proving that diodes became hot enough to melt PCM

16	Electronics: transfer electricity from PV panel	short circuit	no power to diodes	10	wire connection to pot	a) Do not include too many diodes b) Preliminary electrical analysis and testing c)visual inspection of system prior to assembly	2	Customer would notice there was no power	1	20	
17		lose connection	no power to diodes	10	human interference or shorting	Safe practice/exercising caution around apparatus	3	Customer would notice there was no power	1	30	
18	Electronics: connect diodes, chargers to PV panel	connections break	diodes do not heat	10	human interference or shorting	Safe practice/exercising caution around apparatus	3	Customer would notice there was no power	1	30	
19	Electronics: prevent diodes from overheating	diodes overheat	a) diode and circuit failure b) no heat supplied	8	bimetal switch does not engage	making sure bimetal switch is functioning properly	2	Customer would notice there was no power/Through thermal testing we would see if this would be a problem	2	32	
20	General: connect pot structure	jb weld is ineffective in joining the pots	contamination may occur	8	not enough JB weld was used or improper geometry	Using enough JB weld and double checking geometry/assembly issues during manufacturing	3	A) Visual inspection during testing B) Customer would also notice this issue	2	48	
21	General: connect diodes to pot	lose diode connection	food will not get cooked properly	8	diodes weaken and loosen which leads to disconnection	Using proper amount of JB weld to attach diodes to inner pot	3	Customer would notice undercooked food	1	24	
22	General: connect wires and diode chain	solder melts	a) diodes disconnect from each other (Power loss) b) solder contaminates PCM	7	solder gets too hot	Making sure solder does not reach 170 degrees (melting temp)	5	Customer would notice if the power was compromised but the aspect of the solder slightly contaminating the PCM is somewhat harder	5	175	This is one area that we must test heavily due to the aspect of fatigue and cyclical loosening of the diodes from the solder melting slightly and resolidifying
23	General: Hold housing together	Components collapse or separate	Entire structure and all functions are compromised	10	Outside Force/Misuse	Exercising caution around device	2	It would be pretty clear to the customer if components separated	1	20	

Appendix L: First Prototype Indented Bill of Materials

Bill of Materials	
Project:	ISEC w/ TS

Part No.	Description: Level 0	Description: Level 1	Description: Level 2	Description: Level 3	Vendor	Quantity [Units]	Cost/Unit [$/Unit]
10000	Full Assembly						
10100		Lid Subassembly			-		
10101			Disk		Rose Metal Products	1	13.99
10102			Handle		Home Depot	1	4.28
10200		Concentric Pot Subassembly			-		
10201			Flange Extension		SEE PN 10101		
10202			Diode Chain		-		
1N5408				Diode	Sponsor (Mouser Electronics)	30	0.132
KSD9700				Bimetallic Switch	Sponsor (Ebay)	1	1.38
55231				Wire	Sponsor (Grand General)	1	11.7
21945				Solder	Sponsor (Alpha Metals)	1	18.48
10200 Item 1			External Pot		Sponsor (Amazon)	1	6.65
10200 Item 2			Internal Pot		Sponsor (Amazon)	1	6.65
8265			JB Weld		Sponsor (JB Weld)	1	7.99
8297			JB Weld High Heat		JB Weld	1	8.15
844197026012			Erythritol		VitaCost	3	13.99
10000 Item 1		Fiberglass Insulation			Sponsor (Owens Corning)	1	15
LF3554		Foam Cooler			Lifoam	1	12.97
					Total Parts	44	Total Cost

Appendix M: Part Supplier List for Both Prototypes

As mentioned in the report, many of the materials used to construct our design were readily available to us from previous iterations conducted by our sponsor. As a result, the team did not have to purchase many components. For informational purposes the following links are provided and correspond to comparable, if not, the exact supplier we purchased our components from.

Erythritol: https://www.bio.vu.nl/~microb/Protocols/chemicals/MSDS/erytritol.pdf

First Prototype Pots: https://www.amazon.in/Million-Container-Anodised-Aluminium-Cookware/dp/B07K7G69VH/ref=sr_1_1?s=kitchen&ie=UTF8&qid=1549231468&sr=1-1&keywords=aluminium+bhagona

Sheet Metal: https://www.amazon.com/RMP-063-3003-Aluminum-Sheet/dp/B075SH3TCN/ref=sr_1_8?ie=UTF8&qid=1546977855&sr=8-8&keywords=aluminum+sheet+metal

Rectifier Diode: https://www.vishay.com/docs/88516/1n5400.pdf

Bi-metallic Switch: https://www.ebay.com/itm/KSD9700-Temperature-Switch-Thermostat-Thermal-Protector-Normally-Closed-Open-/292110026379

JB Weld:

Regular: https://cdn.shopify.com/s/files/1/0411/5921/files/Steel_Reinforced_Epoxy_Twin_Tubes.pdf?785811878289892783

High Heat: https://cdn.shopify.com/s/files/1/0411/5921/files/Epoxy_Putty_Stick_-_High_Heat_FINAL.pdf?15720338654580686515

Solder: https://www.amazon.com/Flo-Temp-Lead-Free-Electrical-Solder-21945/dp/B000G35N26

Wires: https://www.amazon.com/Grand-General-55231-16-Gauge-Primary/dp/B00INVEUS6

Foam Cooler: https://www.walmart.com/ip/Lifoam-48-Can-Premium-Cooler-Huskee-Hercules/16537216

Fiberglass Insulation: https://www.homedepot.com/p/Johns-Manville-R-13-Kraft-Faced-Fiberglass-Insulation-Roll-15-in-x-32-ft-B1284/100317834

Plaster of Paris: https://activaproducts.com/products/8-x-180-rigid-wrap-plaster-cloth

Rivet Gun and Rivets: https://www.homedepot.com/p/TEKTON-Rivet-Gun-with-40-Rivets-6555/207014968

Metal Grate: https://www.homedepot.com/p/Everbilt-24-in-x-3-4-in-x-24-in-Plain-Expanded-Metal-Sheet-801427/204225784

Thermocouples: https://www.amazon.com/STARVAST-Thermocouple-Temperature-50-400%C2%B0C-58-752%C2%B0F/dp/B07NQJLW6R/ref=sr_1_1_sspa?crid=28D5AMGIH5DC9&keywords=5+pcs+3m+k+type&qid=1559279160&s=gateway&sprefix=5pcs+3M+%2Caps%2C183&sr=8-1-spons&psc=1

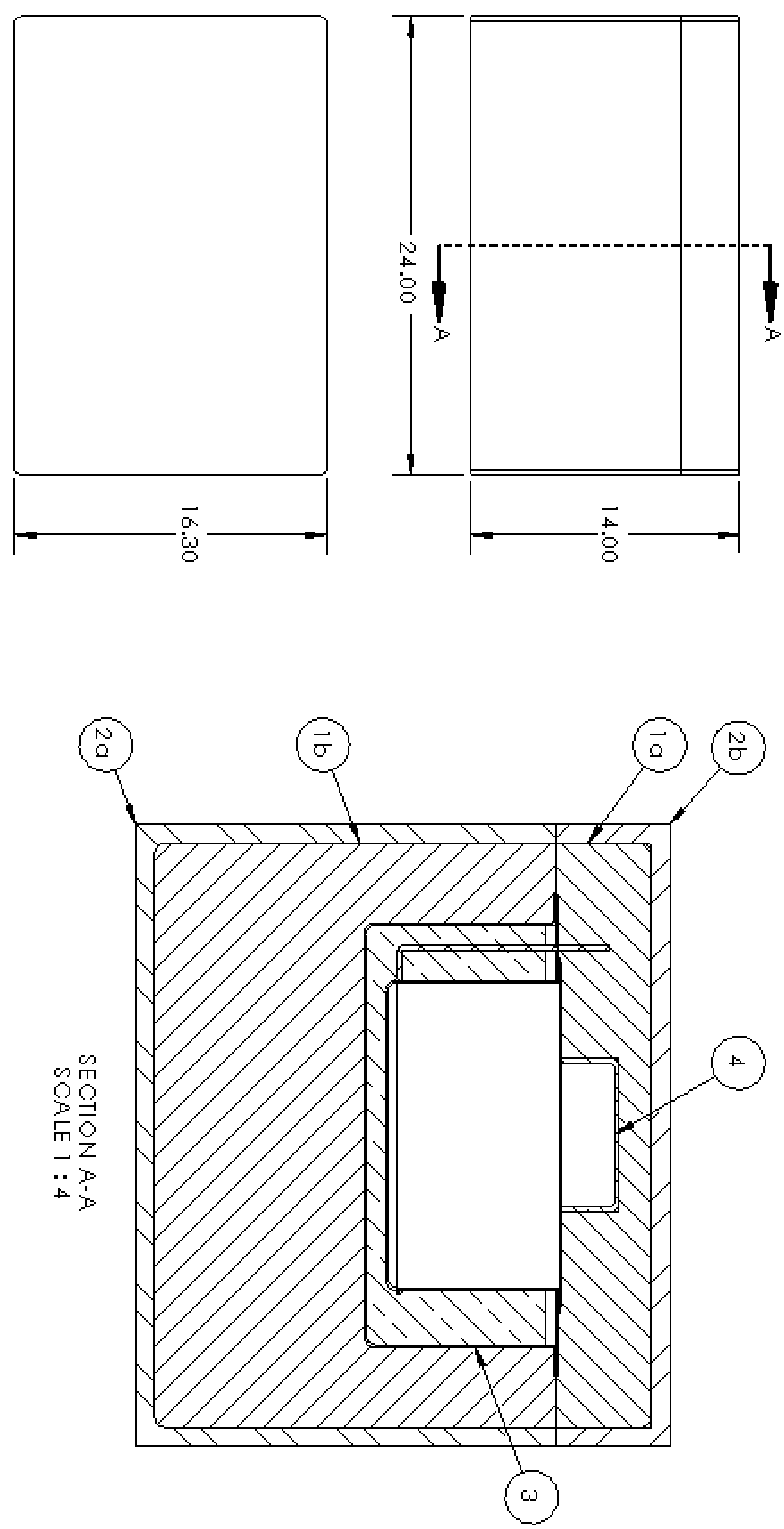
Second Prototype Pots: https://www.amazon.com/KINDEN-Stainless-Composite-Pressure-Preparation/dp/B07CNRCYW5

Cylindrical Housing: https://www.homedepot.com/p/Rubbermaid-Roughneck-20-Gal-Black-Round-Trash-Can-with-Lid-FG289200BLA/100656639

Velcro Strips: https://www.homedepot.com/p/VELCRO-Brand-4-in-x-2-in-Industrial-Strength-Extreme-Strip-Black-91839/205185812?keyword=91839&semanticToken=203t0000111_10224229576255_9d83+203t0000111+%3E++st%3A%7B91839%7D%3Ast+cnn%3A%7B4%3A1%7D+cnr%3A%7B8%3A0%7D+cn1%3A%7B5%3A0%7D+cnd%3A%7B6%3A0%7D+f%3A%7Bb%7D+vc%3A%7B1%7D+oos%3A%7B0%3A1%7D+dln%3A%7B562958%7D+tgr%3A%7BRelaxed+match%7D+qu%3A%7B91839%7D%3Aqu

Nylon Strap: https://www.amazon.com/Straps-JCHL-Capacity-Lifting-Recovery/dp/B07GB1BG7D/ref=sr_1_15?keywords=nylon%2Bstrap&qid=1559279923&s=gateway&sr=8-15&th=1

APPENDIX N: First Prototype Drawing Package

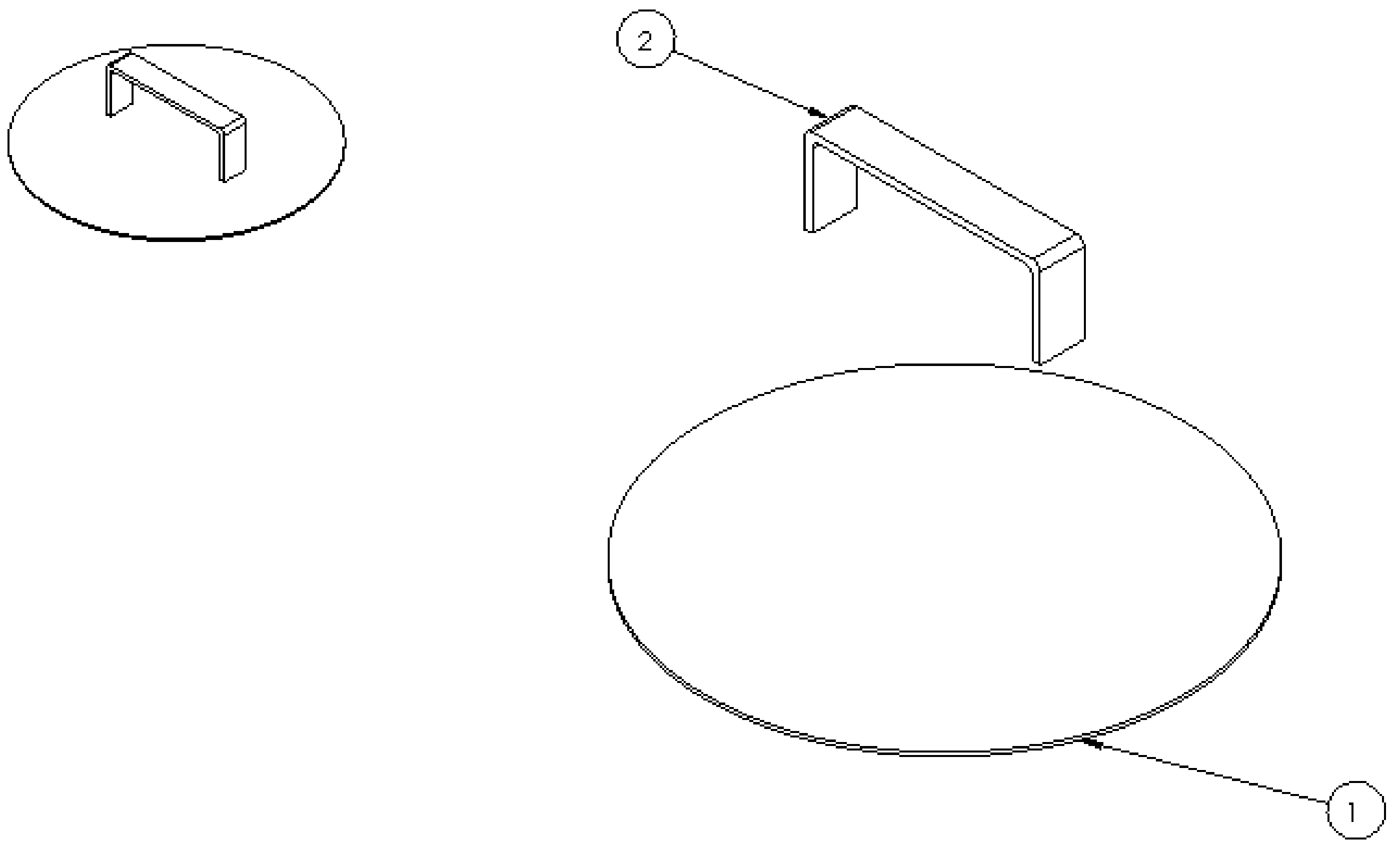


NOTES
UNLESS OTHERWISE SPECIFIED:
1) ALL DIMS IN INCHES

ASSEMBLY NOTES
1) FIBERGLASS INSULATION PACKED AROUND CONCENTRIC POT AND LID SUBASSEMBLIES WITHIN STYROFOAM COOLER

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1a	10000 Item 1-Top	Fiberglass Insulation	1
1b	10000 Item 1-Bottom	Fiberglass Insulation	1
2a	LF3554-Bottom	Styrofoam Cooler Bottom	1
2b	LF3554-Top	Styrofoam Cooler Top	1
4	10100	Lid Subassembly	1
3	10200	Concentric Pots Subassembly	1

Cal Poly Mechanical Engineering	Lab Section: 05	Assignment #	Title: ISEC w/ TS FULL ASSEMBLY	Drwn. by: MATTHEW WEEMAN
ME 429 - W 2019	Dwg. #: 10000	Nxt Asb: 10100	Date: 02/05/2019 Scale: 1:8	Chkd. by: NATE CHRISTLER

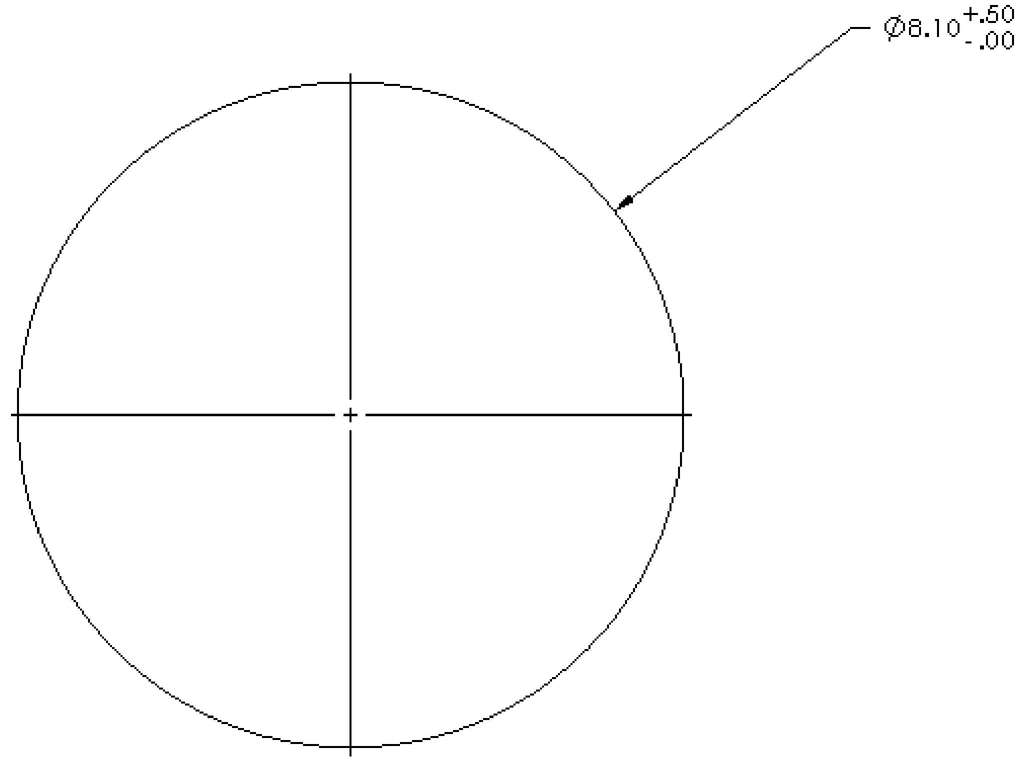


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10101	Disk	1
2	10102	Handle	1

Cal Poly Mechanical Engineering	Lab Section: 03	Assignment #	Title: LID SUBASSEMBLY	Drwn. By: MATTHEW WEEMAN
ME 429 - W 2019	Dwg. #: 10100	Nxt Asb: 10200	Date: 02/03/2019 / Scale: 1:2	Chkd. By: NATE CHRISTLER

NOTES
UNLESS OTHERWISE SPECIFIED:
1) ALL DIMS IN INCHES

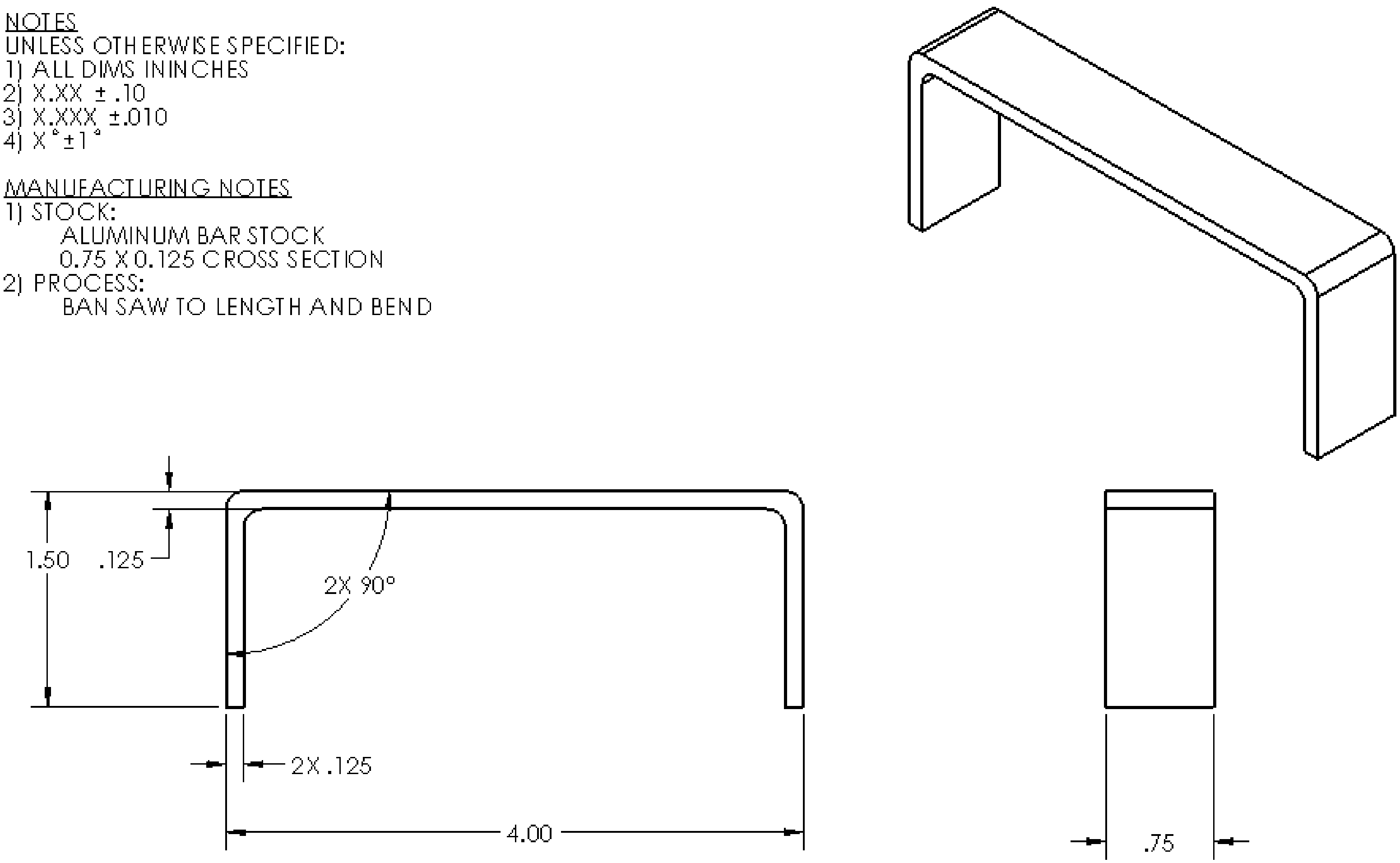
MANUFATURING NOTES
1) STOCK:
ALUMINUM SHEET METAL
14 GAUGE
2) PROCESS:
WATER JET CUT



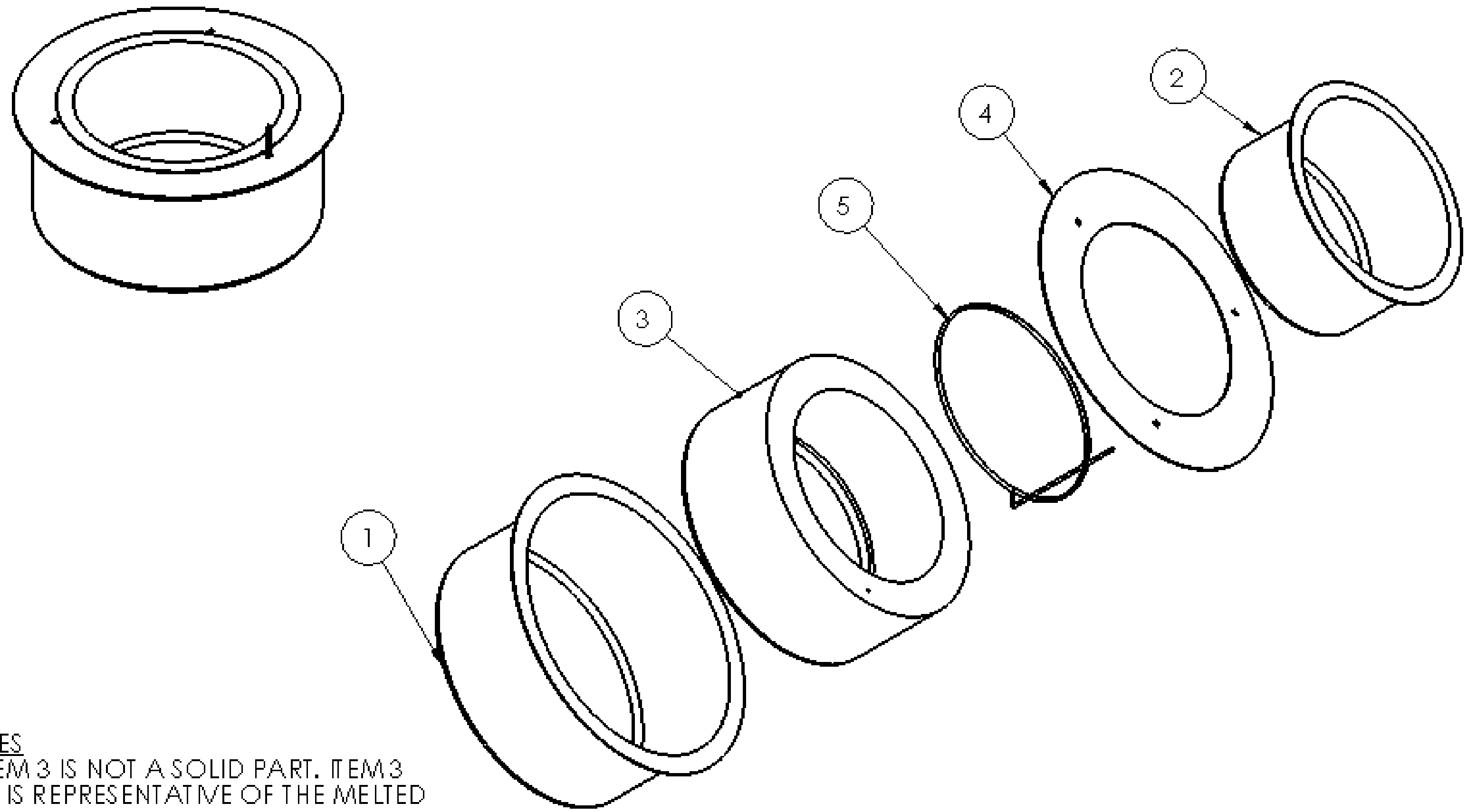
Cal Poly Mechanical Engineering	Lab Section: 03	Assignment #	Title: DISK	Drwn. By: MATTHEW WEEMAN
ME 429 - W 2019	Dwg. #: 10101	Nxt Asb: N/A	Date: 02/03/2019 · Scale: 1:2	Chkd. By: NATE CHRISTLER

NOTES
UNLESS OTHERWISE SPECIFIED:
1) ALL DIMS IN INCHES
2) X.XX ± .10
3) X.XXX ±.010
4) X° ±1°

MANUFACTURING NOTES
1) STOCK:
ALUMINUM BAR STOCK
0.75 X 0.125 CROSS SECTION
2) PROCESS:
BAN SAW TO LENGTH AND BEND



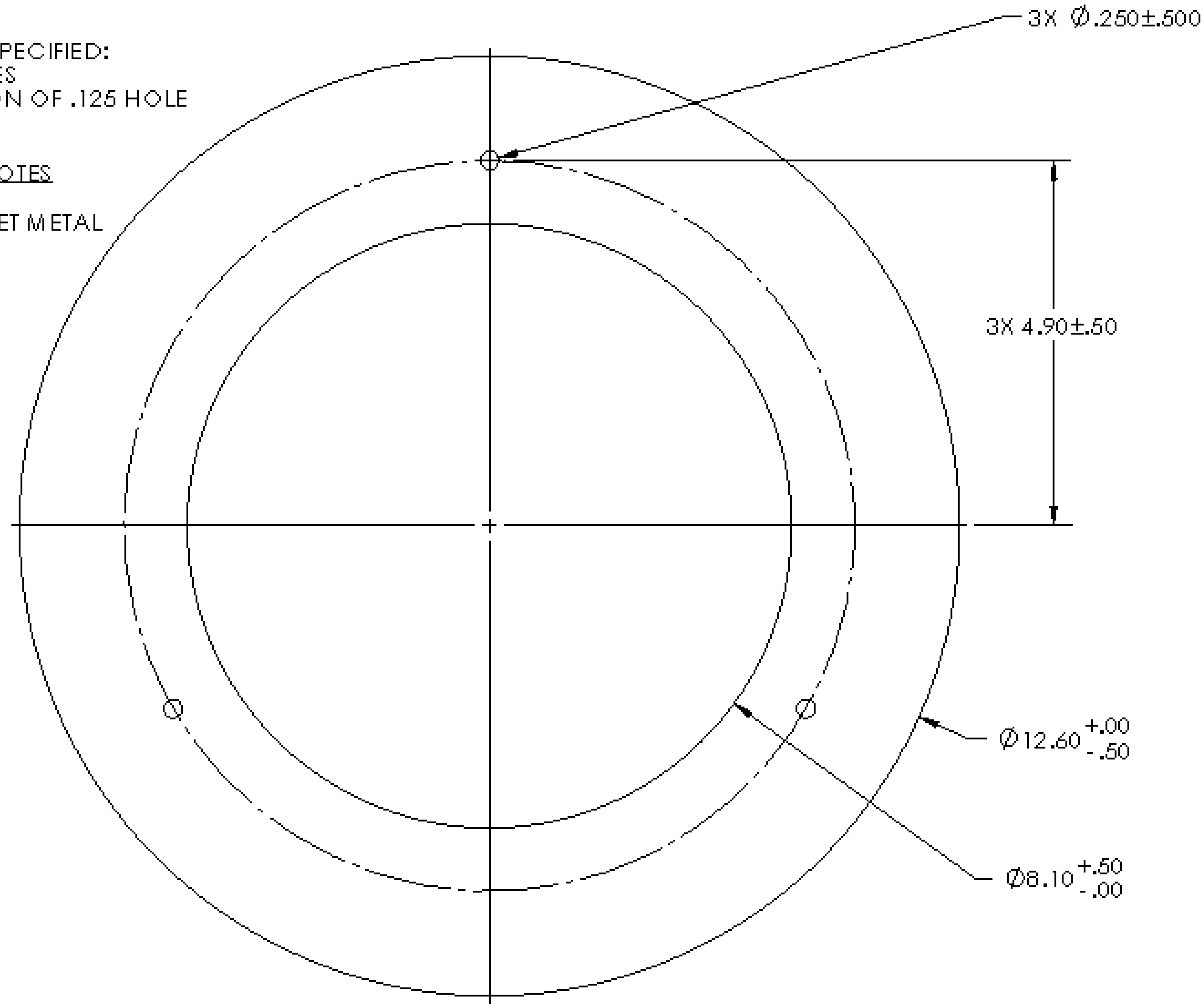
Cal Poly Mechanical Engineering ME 429 - W 2019	Lab Section: 05	Assignment #	Title: HANDLE		Drwn. By: MATTHEW WEEMAN
	Dwg. #: 10102	Nxt Asb: N/A	Date: 02/05/2019	Scale: 1:1	Chkd. By: NATE CHRISTLER



NOTES
1) ITEM 3 IS NOT A SOLID PART. ITEM 3 IS REPRESENTATIVE OF THE MELTED ERYTHRITOL THAT IS POURED INTO THE CAVITY BETWEEN THE INTERNAL AND EXTERNAL POTS

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	10200 Item 1	External Pot	1
2	10200 Item 2	Internal Pot	1
3	844197026012	Erythritol	1
4	10201	Flange	1
5	10202	Diode Chain	1

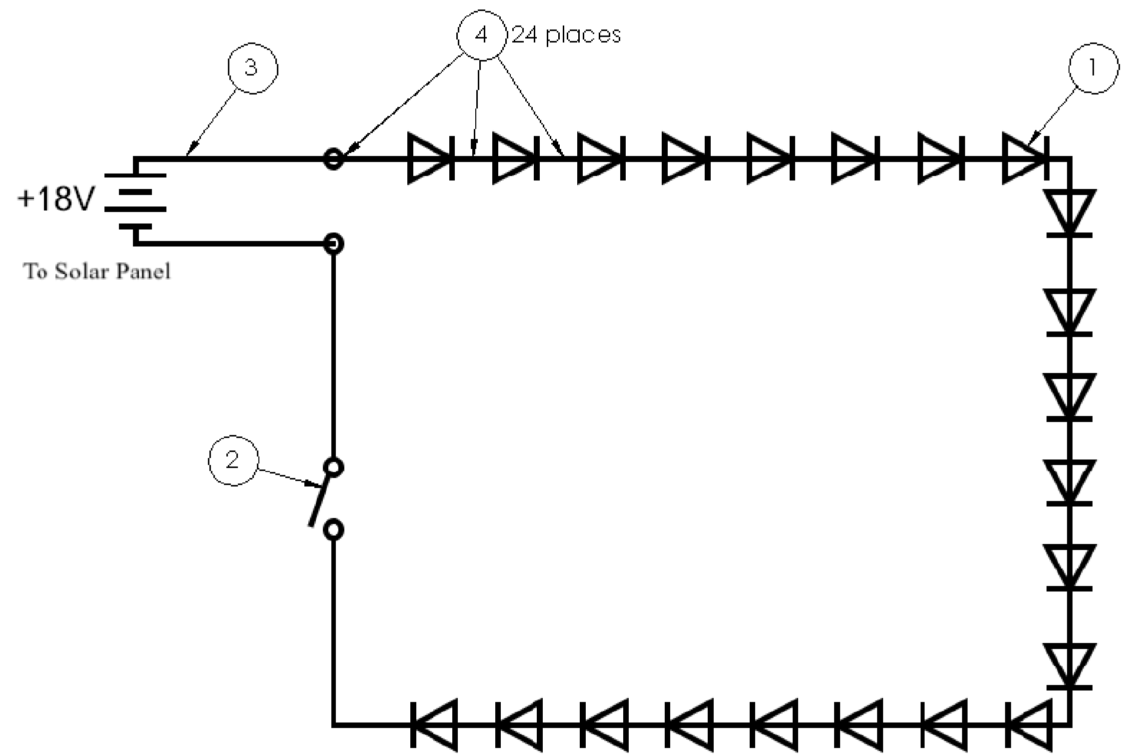
Cal Poly Mechanical Engineering ME 429 - W 2019	Lab Section: 05	Assignment #	Title: CONCETRIC POT SUBASSEMBLY		Drwn. By: MATTHEW WEEMAN
	Dwg. #: 10200	Nxt Asb: N/A	Date: 02/05/2019	Scale: 1:6	Chkd. By: NATE CHRISTLER



NOTES
UNLESS OTHERWISE SPECIFIED:
1) ALL DIMS IN INCHES
2) ANGULAR POSITION OF .125 HOLE NON-CRITICAL

MANUFACTURING NOTES
1) STOCK:
ALUMINUM SHEET METAL
14 GAUGE
2) PROCESS:
WATER JET CUT

Cal Poly Mechanical Engineering ME 429 - W 2019	Lab Section: 05	Assignment #	Title: FLANGE EXTENSION		Drwn. By: MATTHEW WEEMAN
	Dwg. #: 10201	Nxt Asb: N/A	Date: 02/05/2019	Scale: 1:2	Chkd. By: NATE CHRISTLER



Manufacturing Note
1) Solder must be applied between all adjacent components and wires

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1N5408	1N5408 Rectifier Diode	22
2	KSD9700	Bi-metallic Switch (160 deg C)	1
3	55231	16 Gauge Wire Lead (1 ft)	2
4	21945	Lead-free Rosin Core Solder	1

Cal Poly Mechanical Engineering	Lab Section: 5	Assignment #	Title: Diode Chain Circuit Diagram		Drwn. By: Nate Christler
ME 429 - Winter 2019	Dwg. #: 10202	Nxt Asb: N/A	Date: 2/2/2019	Scale: 1:1	Chkd. By: Matthew Weeman

Appendix O: Design Verification Plan

Charge Test

Goal: Verify that the ISEC is capable of melting all the PCM and bringing the PCM to full charge temperature in the design charge time.

Equipment: A DC power supply or a 100 Watt solar panel, a voltage and current datalogger (solar testing only), ISEC with embedded PCM thermocouples, a 4 port thermocouple reader and datalogger, and a stopwatch.

Procedure:

1. Connect the embedded thermocouples to the 4-port thermocouple reader and datalogger and verify the thermocouples are reading accurate temperatures.
2. If performing a solar test, setup a voltage and current datalogger to measure the voltage and current from the solar panel.
3. Connect the ISEC to the solar panel or power source. If using a DC power source, increase the voltage until the power coming from the source is 100W. Start the stopwatch once the ISEC is connected to power.
4. While the ISEC is charging, periodically check the thermocouple readings to ensure the ISEC is charging without issues. For tests using a DC power source, also monitor the input current and voltage. Record current and voltage at least every half hour and adjust voltage as necessary to maintain a constant power of 100W.
5. Allow the ISEC to charge until: a) a set temperature is reached, b) a set charging time has passed, or c) the bimetallic switch has automatically disconnected to the power.
6. If it is desired to use this test to confirm the design charge time, the time should be recorded when the average PCM temperature is equal to the design full-charge temperature (150°C)

Boil Test

Goal: Verify that the ISEC is capable of boiling water within 20 minutes and then maintaining that boil for at least an hour

Equipment: A DC power supply or a 100 Watt solar panel, a voltage and current datalogger (solar testing only), ISEC with embedded PCM thermocouples, a 4 port thermocouple reader and datalogger, an additional thermocouple and thermocouple reader, a stopwatch, a digital scale, and containers for holding water.

Procedure:

1. Charge ISEC to desired temperature or until bimetallic switch turns off.
2. While ISEC is charging, measure out a desired mass of water to boil using the digital scale.
3. Once the ISEC is fully charged, quickly measure the starting temperature of the water, open the ISEC, add the water to the ISEC’s cooking cavity along with a thermocouple to monitor the temperature of the water, and reseal the ISEC. Note the time when the water was added to the ISEC.
4. Monitor the temperature of the water as well as the temperature of the embedded PCM thermocouples.
5. Once the temperature of the water is reading at or near 100°C, note the time and quickly open the ISEC to visually verify whether or not the water is in fact boiling.

6. Continue to monitor temperatures until after the water has ceased boiling and record the duration of said boil.
7. Note, this test can be performed with or without power to cooking with and without sunlight.

Cooldown Test

Goal: Experimentally determine the thermal resistance of our insulation.
Equipment: A DC power supply or a 100W solar panel, ISEC with embedded PCM thermocouples, and a 4 port thermocouple reader and datalogger
Procedure:

1. Charge up ISEC to desired temperature or until bimetallic switch turns off
2. Cut off power to the ISEC and allow thermocouples to continue recording PCM temperature until the PCM has returned to ambient temperature.
3. From the cooling curve, determine the R-Value of the ISEC's insulation.

Efficiency Test Procedure

Goal: Quantify the efficiency of the ISEC.
Equipment: A DC power supply or a 100W solar panel, ISEC with embedded PCM thermocouples, a 4-port thermocouple reader and datalogger, an additional thermocouple and thermocouple reader, a digital scale, containers for measuring water, and possibly ice if required.

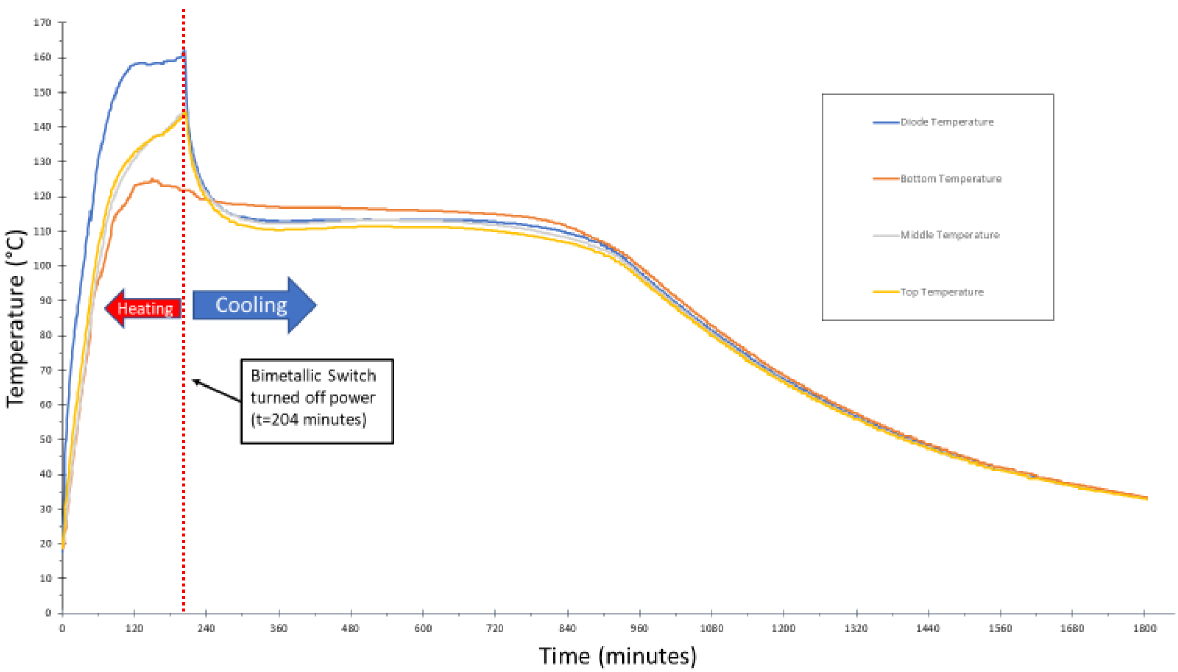
Procedure:

1. Charge ISEC to desired temperature or until bimetallic switch turns off.
2. When the ISEC is nearly done charging, measure out a desired mass of water on the digital scale. Alternatively, measure out a mass of ice from an ice water bath in place of water. The goal here is to use the right amount of water or ice such that the end temperature of the water will be near 100°C without achieving boiling. Ideally, you should have a good estimate of the required thermal mass from earlier tests. But if the correct thermal mass is not accurately known, you can initially start with less water or ice than required and add more as the water approaches boiling.
3. Once the ISEC is fully charged, quickly measure the starting temperature of the water (if melting ice is being used instead there is no need to measure the temperature), open the ISEC, add the water (or ice) to the ISEC's cooking cavity along with a thermocouple to monitor the temperature of the water, and reseal the ISEC. Note the time when the water (or ice) was added to the ISEC.
4. Monitor the temperature of the water as well as the temperature of the embedded PCM thermocouples.
5. Once the water reaches a maximum temperature, note said maximum.
6. The efficiency test should be preformed with the power disconnected.
7. From the mass of water or ice added and the temperature change, calculate energy delivered to the water. From the input current and voltage, calculate the total energy delivered to the ISEC. Divide the energy delivered to the water by the energy delivered to the ISEC to determine the efficiency.

Appendix P: Risk Assessment

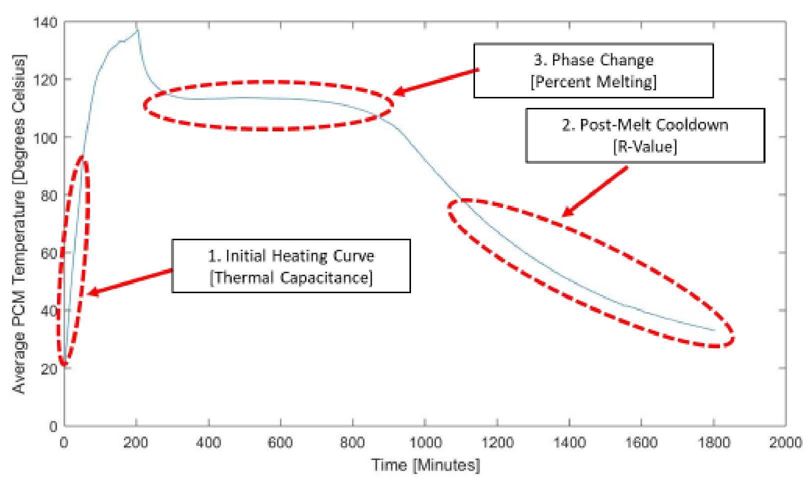
	Item Id	User	Task	Hazard Category	Hazard	Cause/Failure Mode	Photos	Severity	Probability	Risk Level	Risk Reduction Measures
1	1-1-1	Consumer	Cooking	food safety	contaminant materials (metal, plastic, cloth, etc)	Contamination of Food		Moderate	Likely	Medium	Redesign Final Prototype with Food Safe Insulation
2	1-1-2	Consumer	Cooking	food safety	foodborne pathogens	Undercooked Food		Serious	Unlikely	Medium	Instruct User To Check Temperature
3	1-1-3	Consumer	Cooking	heat / temperature	burns / scalds	User Burned by Pot		Moderate	Unlikely	Low	
4	1-2-1	Consumer	Cleaning	mechanical	cutting / severing	User Cut During Cleaning of Pot		Minor	Unlikely	Negligible	
5	1-3-1	Consumer	Simple Maintenance	mechanical	cutting / severing	User Cut While Opening Pot		Moderate	Unlikely	Low	
6	1-4-1	Consumer	Charging PCM	heat / temperature	burns / scalds	User Burns Himself on PCM		Moderate	Remote	Negligible	
7	1-5-1	Consumer	Connecting Wires	electrical / electronic	Electrical Shock	User Gets Shocked From Wires		Minor	Unlikely	Negligible	
8	2-1-1	Manufacturer	Soldering	heat / temperature	burns / scalds	Solder Operator Gets Burned		Moderate	Unlikely	Low	
9	2-1-2	Manufacturer	Soldering	chemical	Exposure To Lead	Solder Operator Exposed to Lead		Moderate	Likely	Medium	Operator Wears PPE
10	2-2-1	Manufacturer	Cutting	mechanical	cutting / severing	Cutting Operator Gets Cut		Serious	Unlikely	Medium	
11	2-3-1	Manufacturer	Welding	heat / temperature	Welding	Welding Operator Has Issue					
12	2-4-1	Manufacturer	Melting PCM	heat / temperature	burns / scalds	Operator Burned From Melted PCM		Moderate	Unlikely	Low	
13	2-5-1	Manufacturer	Assembly	environmental / industrial hygiene	irritants	Assembler Exposed to Fiberglass Insulation		Moderate	Likely	Medium	Assembler Wears PPE/Mask
14	2-5-2	Manufacturer	Assembly	ventilation / confined space	air contaminants	Assembler Exposed to Airborne Fiberglass Insulation		Moderate	Likely	Medium	
15	2-6-1	Manufacturer	Testing	heat / temperature	burns / scalds	Tester Burned		Moderate	Unlikely	Low	
16	2-7-1	Manufacturer	Drilling	mechanical	cutting / severing	Drill Operator Gets Cut		Moderate	Remote	Negligible	
17	3-1	Senior Project Team	Carrying	<None>	<None>						
18	3-2	Senior Project Team	Maintenance	<None>	<None>						
19	3-3	Senior Project Team	Charging PCM	<None>	<None>						
20	3-4	Senior Project Team	Connecting Wires	<None>	<None>						
21	3-5	Senior Project Team	Soldering	<None>	<None>						
22	3-6	Senior Project Team	Cutting	<None>	<None>						
23	3-7	Senior Project Team	Melting PCM	<None>	<None>						
24	3-8-1	Senior Project Team	Epoxying	environmental / industrial hygiene	irritants	Students Get Epoxy on Skin		Minor	Likely	Low	
25	3-8-2	Senior Project Team	Epoxying	environmental / industrial hygiene	contamination	Students Get Epoxy Inside Pot		Moderate	Unlikely	Low	
26	3-9	Senior Project Team	Assembly	<None>	<None>						
27	3-10	Senior Project Team	Testing	<None>	<None>						
28	3-11	Senior Project Team	Drilling	<None>	<None>						
29	4-1-1	Bystander	Potentially Interfering With Device	slips / trips / falls	trip	Blunt trauma from fall		Minor	Unlikely	Negligible	
30	4-1-2	Bystander	Potentially Interfering With Device	fire and explosions	uncontrolled ignition sources	Fire spreads and can burn surrounding area and people		Catastrophic	Unlikely	Medium	Caution on Outside of Housing to Keep Flammable Materials Away / Thorough Inspection During Testing

Appendix Q: Analysis of Cooldown Test 1



*Tave is simple mean of bottom, middle, and top thermocouples.

The diode thermocouple was excluded as it was a localized hotspot and therefore not representative of the PCM as a whole



1. Thermal Capacitance

Graphical Analysis

Slope=1.4512°C/min

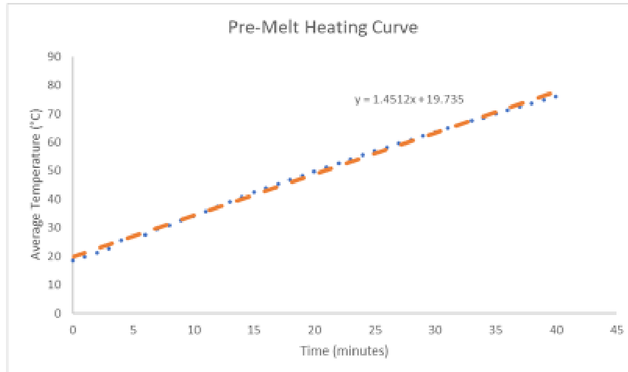
100 Watts of power is causing our ISEC to increase in temperature at a rate of 1.4512 degrees Celsius per minute.

$$q = C\dot{T}$$

$$C = \frac{q}{\dot{T}} = \frac{100W}{1.4512\,{}^{\circ}\mathrm{C}/_{min} \cdot (\frac{min}{60s})}$$

$$C = 4130\left[\frac{J}{{}^{\circ}\mathrm{C}}\right]$$

The heat capacitance of our device is 4130 Joules per degree Celsius while the erythritol is solid



1. Thermal Capacitance

Expected Capacitance by Mass

ISEC weighs 2.7kg

Contains 1.8kg of erythritol

Other .9kg of our ISEC can be attributed to aluminum pots, diodes, JB weld, wires and other small components

$$c_e = 1.38J/(g \cdot {}^{\circ}\mathrm{C})$$

$$c_{Al} = .90J/(g \cdot {}^{\circ}\mathrm{C})$$

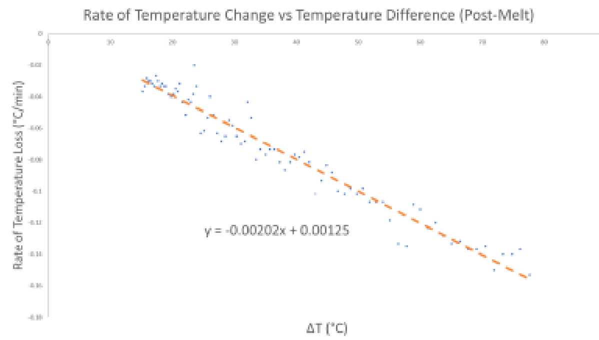
$$C_{Theory} = 1800g \cdot \frac{1.38J}{g \cdot {}^{\circ}\mathrm{C}} + 900g \cdot \frac{.90J}{g \cdot {}^{\circ}\mathrm{C}} = 3294\left[\frac{J}{{}^{\circ}\mathrm{C}}\right]$$

3294 $\left[\frac{J}{{}^{\circ}\mathrm{C}}\right]$ is significantly less than 4130 $\left[\frac{J}{{}^{\circ}\mathrm{C}}\right]$, but if you take into account the higher temperature erythritol near the diodes (which wasn't included in the average), the added mass of the lid, and inefficiencies due to heat loss, our experimental value seems reasonable. We'll use the average of the two 3700 $\left[\frac{J}{{}^{\circ}\mathrm{C}}\right]$ for our insulation efficiency calculations

2. R-Value

Graphical Analysis

Slope= $\frac{\dot{T}}{\Delta T} = -0.00202\left[\frac{°C/min}{°C}\right]$



For every 1 degree temperature difference between the erythritol and the ambient air 0.00202°C was lost every minute.

i.e. when the erythritol was 78°C (60°C hotter than the environment), the rate of temperature loss was 0.121 degrees Celsius per minute meaning it would take 8.25 minutes to cool down to 77°C.

$$q = C\dot{T} = \frac{\Delta T}{R}$$

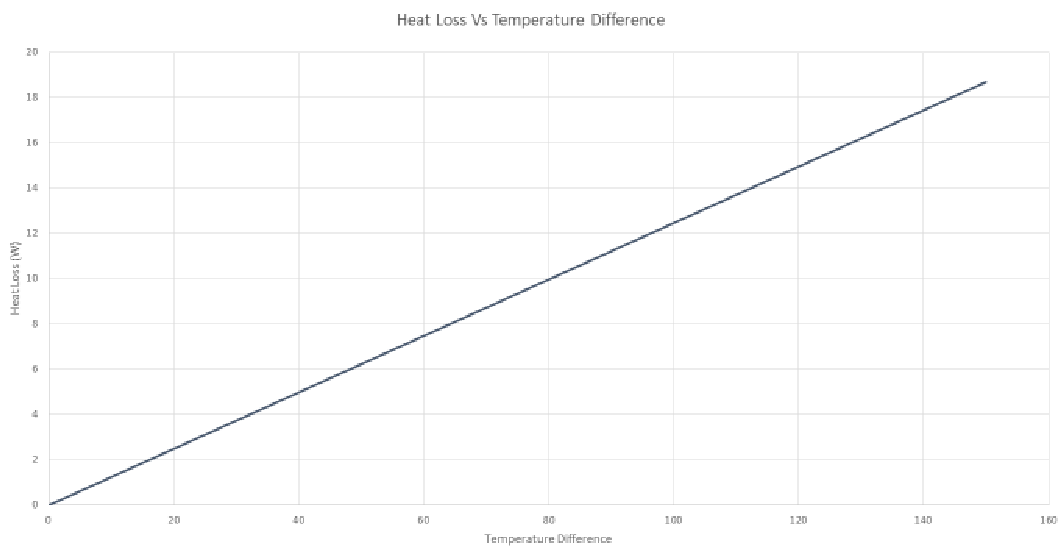
$$R = \frac{\Delta T}{C \cdot \dot{T}} = \frac{1}{3700\left[\frac{J}{°C}\right]} \cdot \frac{1}{0.00202\left[\frac{°C/min}{°C}\right] \cdot \left[\frac{min}{60s}\right]} = 8.03\left[\frac{°C}{W}\right]$$

Predicted R-Value=101
R=x/(A*k)

R=13 for 3.5 inch

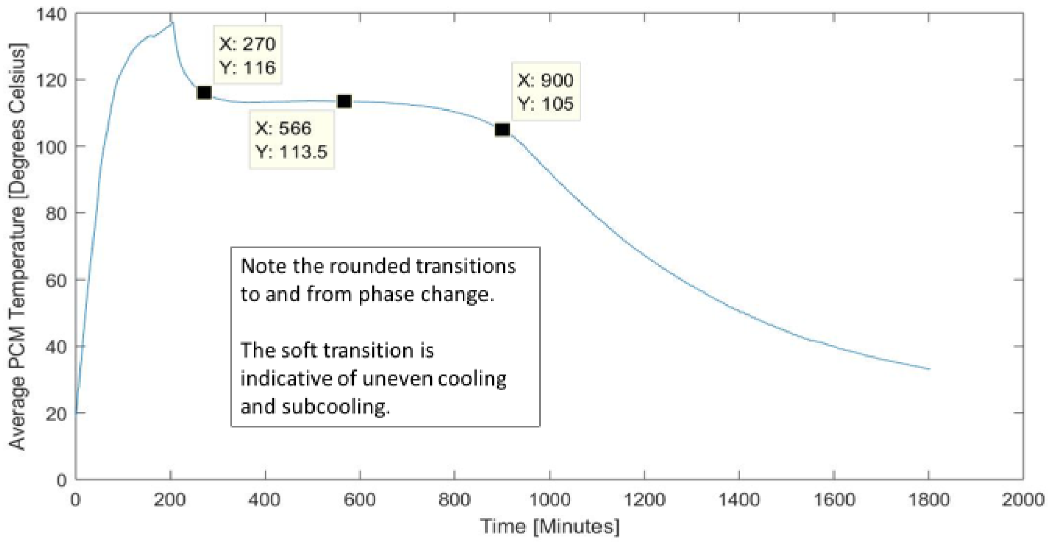
2. R-Value

Equating Results to Heat Loss



3. Percent Melting

Data



3. Percent Melting

Graphical Analysis

Phase Change Duration = 630 minutes
Phase Change Temperature = 113.5C

$$q = \frac{113.5℃ - 18℃}{\left[8.03\frac{℃}{W}\right]} = 11.9W$$

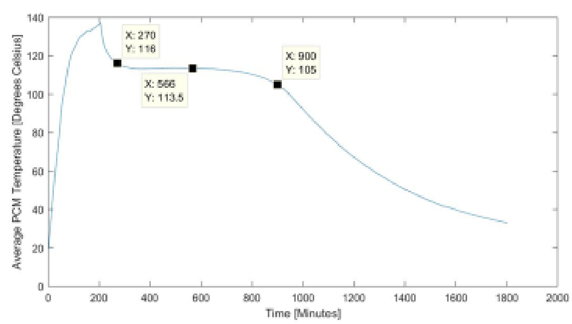
$$E_{melt} = q \cdot t_{melt} = 11.9W \cdot 630min \cdot \frac{60s}{min}$$
$$E_{melt} = 449.6KJ$$

$$h_f = \frac{347KJ}{kg}$$
$$m = 1.8kg$$

$$E_{melt,100\%} = 1.8kg \cdot 347\frac{KJ}{kg} = 625KJ$$

$$\%_{melt} = \frac{449.6KJ}{625KJ} \times 100\% = 72\%$$

From this Analysis, we can assume the bimetallic switch cut power off too early before eyrthritol was fully melted



Appendix R: Second Prototype Indented Bill of Materials

Bill of Materials	
Project:	ISEC w/ TS

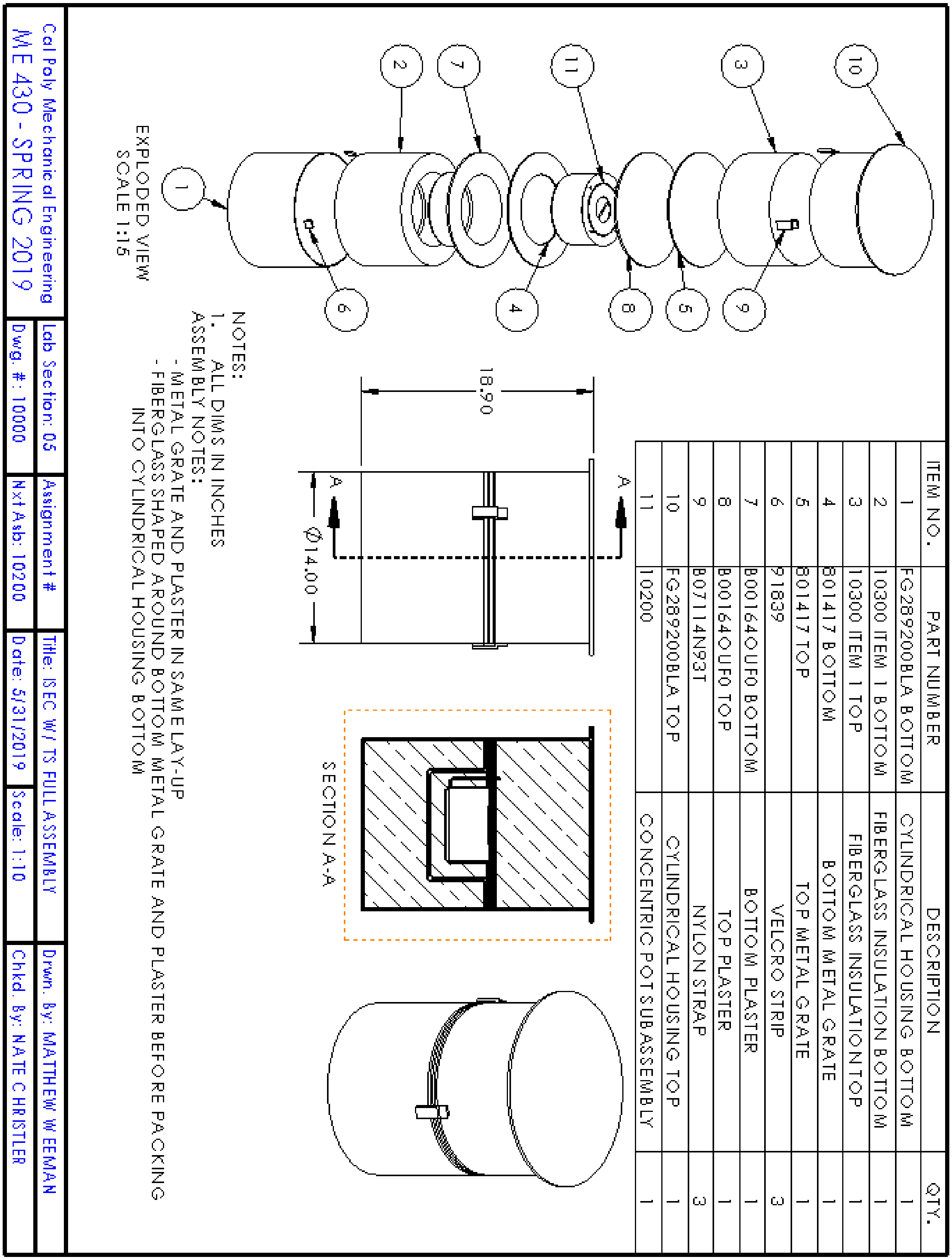
Part No.	Description Level 0	Description Level 1	Description Level 2	Description Level 3	Vendor	Quantity [Units]	Cost/Unit [$/Unit]	Total Part Cost [$]
10000	Full Assembly							
10200		Concentric Pot Subassembly			-			
10201			Flange Extension		Rose Metal Products	1	13.99	13.99
10202			Diode Chain		-			
1N5402				Diode	Sponsor (Mouser Electronics)	30	0.132	3.96
KSD9700				Bimetallic Switch	Sponsor (Ebay)	1	1.38	1.38
55231				Wire	Sponsor (Grand General)	1	11.7	11.7
21945				Solder	Sponsor (Alpha Metals)	1	18.48	18.48
B07CNRCYW5			Concentric Pot Set		KINDEN	1	29.99	29.99
8265			JB Weld		JB Weld	1	7.99	7.99
8297			JB Weld High Heat		JB Weld	1	8.15	8.15
844197026012			Erythritol		VitaCost	2	13.99	27.98
10300		Housing Subassembly			-			
FG289200BLA			Cylindrical Housing		Home Depot	1	12.97	12.97
10300 Item 1			Fiberglass Insulation		Sponsor (Owens Corning)	1	15	15
801417			Metal Grate		Home Depot	1	9.37	9.37
B00164OUF0			Plaster Cloth		Activa	1	18.61	18.61
91839			Velcro Strips		Home Depot	1	4.28	4.28
B07114N93T			Nylon Strap		Tapecraft	1	3	3
					Total Parts	43	Total Cost	186.85

Appendix S: Second Prototype Budget

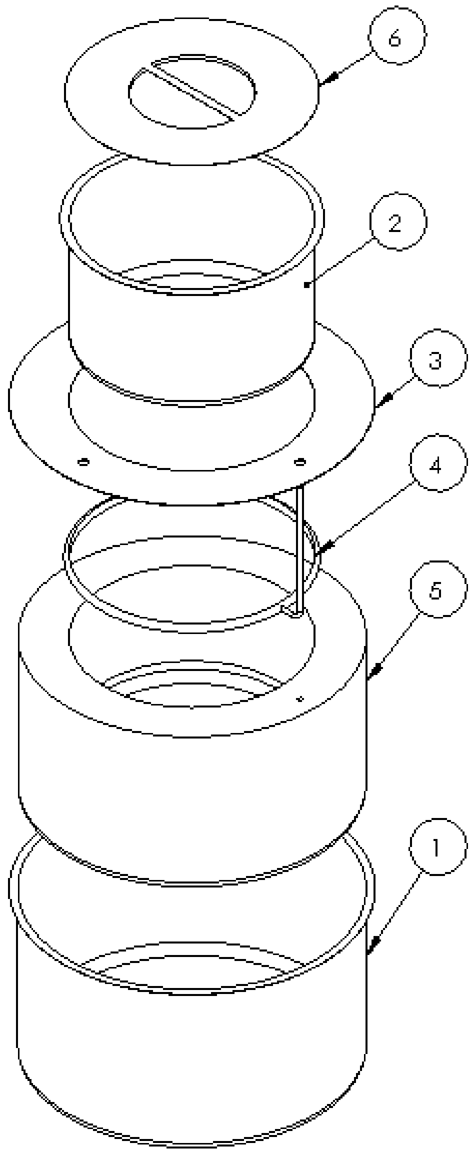
Team 55: InSECTS project budget

Item Description	Vendor	Vendor Part No.	Part No.	Purchase Method	Purchase Date	Recieved Date	Quantity	Cost/Unit	Cost
Concentric Pot Set	Amazon	B07CNRCYW5	B07CNRCYW5	Sponsor	4/16/2019	4/18/2019	1	$29.99	$29.99
Rectifier diode*	Mouser Electronics	1N5402	1N5402	Sponsor	N/A	N/A	30	$0.13	$3.96
Bi-metal switch*	Ebay	KSD9700	KSD9700	Sponsor	N/A	N/A	1	$1.38	$1.38
Wire*	Grand General	55231	55231	Sponsor	N/A	N/A	1	$11.70	$11.70
Solder*	Alpha Metals	21945	21945	Sponsor	N/A	N/A	1	$18.48	$18.48
Erythritol	VitaCost	844197026012	844197026012	Sponsor	11/17/2018	11/19/2018	2	$13.99	$27.98
Insulation*	Owens Corning	N/A	10000 Item 1	Sponsor	N/A	N/A	1	$15.00	$15.00
Cylindrical Housing	Home Depot	FG289200BLA	FG289200BLA	Sponsor	4/6/2019	4/6/2019	1	$12.97	$12.97
Velcro Strips	Home Depot	91839	91839	Sponsor	4/20/2029	4/20/2029	1	$4.28	$4.28
Sheet metal	Rose Metal Products	N/A	10201	Sponsor	4/16/2019	4/18/2019	1	$13.99	$13.99
JB Weld Hi Heat	JB Weld	8297	8297	Sponsor	4/16/2019	4/18/2019	1	$8.15	$8.15
JB Weld	JB Weld	8265	8265	Sponsor	4/16/2019	4/18/2019	1	$7.99	$7.99
Nylon Strap*	Tapecraft	B07114N93T	B07114N93T	Sponsor	N/A	N/A	1	$3.00	$3.00
Metal Grate	Home Depot	801417	801417	Sponsor	4/20/2029	4/20/2029	1	$9.37	$9.37
Plaster Cloth	Activa	B00164OUF0	B00164OUF0	Sponsor	4/16/2019	4/18/2019	1	$18.61	$18.61
Rivet Gun and Rivets	Tekton	6555	N/A (Tooling)	Sponsor	4/16/2019	4/18/2019	1	$12.35	$12.35
Thermocouple 5 pack	ZIJA	B00OLNZ6XI	N/A (Testing)	Sponsor	4/9/2019	4/11/2019	1	$13.99	$13.99
* indicates the sponsor already had the component on hand, prices gathered from representative vendors								Total Cost	$213.19

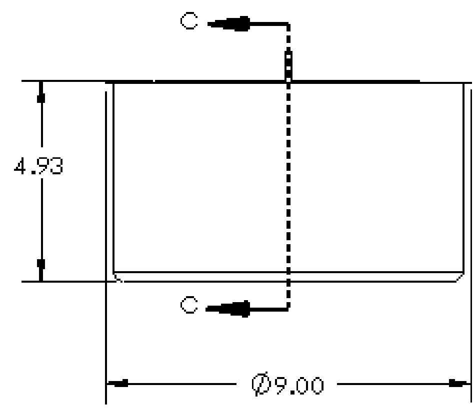
Appendix T: Second Prototype Drawing Package

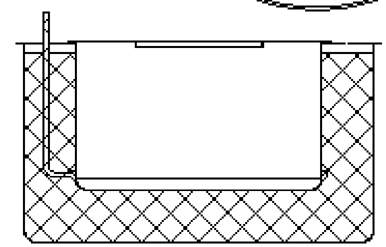


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	FG289200BLA BOTTOM	CYLINDRICAL HOUSING BOTTOM	1
2	10300 ITEM 1 BOTTOM	FIBERGLASS INSULATION BOTTOM	1
3	10300 ITEM 1 TOP	FIBERGLASS INSULATION TOP	1
4	B01417 BOTTOM	BOTTOM METAL GRATE	1
5	B01417 TOP	TOP METAL GRATE	1
6	91839	VELCRO STRIP	3
7	B00164OUFO BOTTOM	BOTTOM PLASTER	1
8	B00164OUFO TOP	TOP PLASTER	1
9	B07114N93T	NYLON STRAP	3
10	FG289200BLA TOP	CYLINDRICAL HOUSING TOP	1
11	10200	CONCENTRIC POT SUBASSEMBLY	1

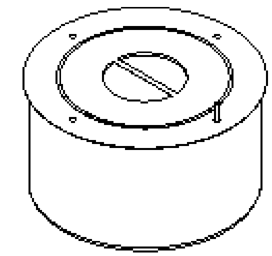


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	B07CNRCYW5 EXTERNAL	EXTERNAL POT	1
2	B07CNRCYW5 INTERNAL	INTERNAL POT	1
3	10201	FLANGE EXTENSION	1
4	10202	DIODE CHAIN	1
5	844197026012	ERYTHRITOL	1
6	B07CNRCYW5 LID	INTERIOR POT LID	1





SECTION C-C

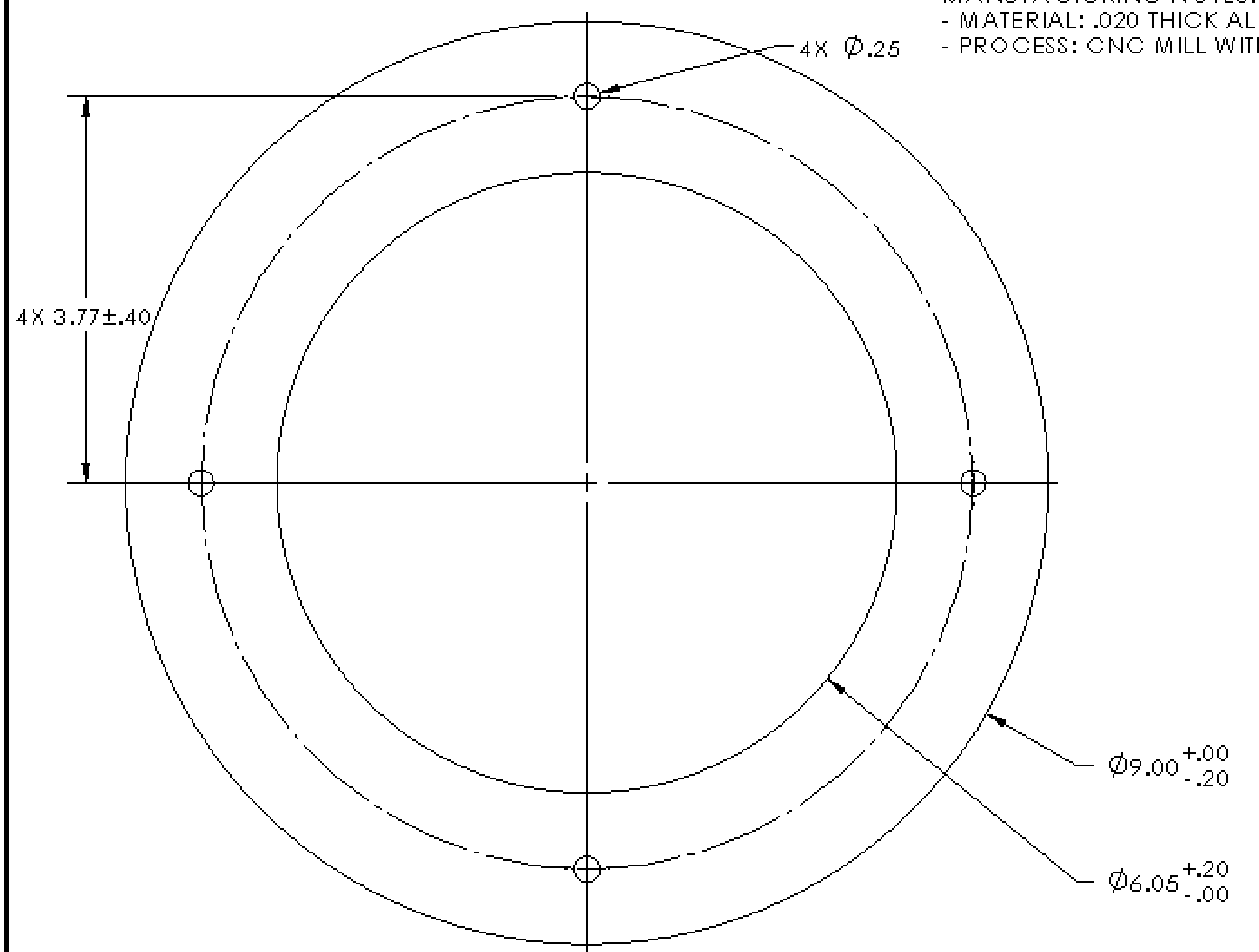


NOTES:
1. ALL DIMS IN INCHES
ASSEMBLY NOTES:
ERYTHRITOL NOT INSERTED AS A SOLID, POURED AS A LIQUID

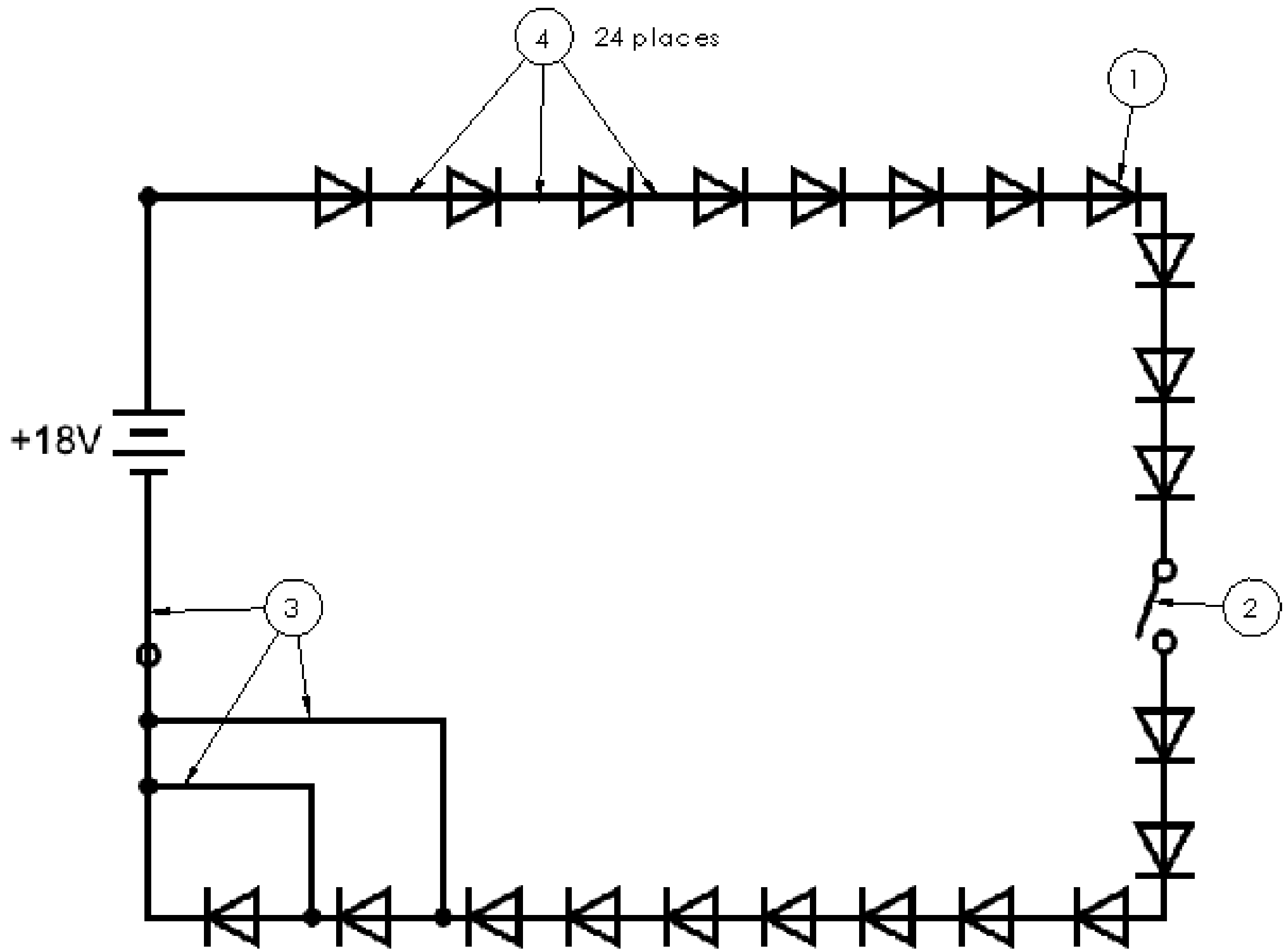
Cal Poly Mechanical Engineering	Lab Section: 05	Assignment #	Title: CONCENTRIC POT SUBASSEM.	Drwn. By: MATTHEW WEEMAN
ME 430 - SPRING 2019	Dwg. #: 10200	Nxt Asb: 10202	Date: 5/31/2019 / Scale: 1:4	Chkd. By: NATE CHRISTLER

NOTE:
1. ALL DIMS IN INCHES
2. ANGULAR POSITION OF .25 HOLES NON-CRITICAL, ROUGHLY EVEN SPACING

MANUFACTURING NOTES:
- MATERIAL: .020 THICK ALUMINUM SHEET METAL
- PROCESS: CNC MILL WITH SACRIFICIAL WOOD



Cal Poly Mechanical Engineering	Lab Section: 05	Assignment #	Title: FLANGE EXTENSION		Drwn. By: MATTHEW WEEMAN
ME 430 - SPRING 2019	Dwg. #: 10201	Nxt Asb: N/A	Date: 5/31/2019	Scale: 2:3	Chkd. By: NATE CHRISTLER



Manufacturing Note
1) Solder must be applied between all adjacent components and wires

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1N5402	1N5402 Rectifier Diode	22
2	KSD9700	Bi-metallic Switch (160 deg C)	1
3	55231	16 Gauge Wire Lead (1 ft)	4
4	21945	Lead-free Rosin Core Solder	1

Cal Poly Mechanical Engineering ME 429 - Winter 2019	Lab Section: 5	Assignment #	Title: Diode Chain Circuit Diagram		Drwn. By: Nate Christler
	Dwg. #: 10202	Nxt Asb: N/A	Date: 5/29/2019	Scale: 1:1	Chkd. By: Matthew Weeman

Appendix U: Operator's Manual

Operators Manual

ISEC surrounded by housing

100 Watt Power Source

Main Safety Hazards:

Exposed wiring from leads leading to power source / solar panel can have up to 100 Watts flowing through them

During charging, pot and or surroundings may be hot to touch

Operator Steps:

1. Load ISEC into exterior housing
2. Connect leads from solar panel to the leads from the ISEC diode chain (ensuring proper polarity)
3. Let ISEC charge (approximately 4-6 hours)
4. Insert food or water and cook to completion (approximately 20-40 minutes to boil water)
5. Detach the solar panel leads
6. Caution: contents may be hot!
7. As needed, remove device from housing to clean

Appendix V: Uncertainty Calculation for Efficiency (DC Power Source)

scale Resolution +/- .5g

thermocouple Reader resolution +/- .05°C

thermocouples: +/- 2.5°C

Power source resolution +/- .05A

+/- .05V

time resolution +/- .5 minute.

$$\eta = \frac{m c T_f + m h_f}{V \cdot I \cdot t}$$

$m = 1212g$

$c = 4.2 \left[\frac{J}{g°C}\right]$

$$R = \frac{X \cdot Y}{Z}$$

$h_f = 334 \frac{J}{g}$

$T_f = 91.6°C$

$$\eta = \frac{m\,(c T_f + h_f)}{V \cdot I \cdot t}$$

$V = 17.0\,V$

$I = 5.8\,A$

$t = 384\,min$

$\eta = .383$

$u_m = 4.125 \times 10^{-4}$

$u_T = .0273$

$u_V = .00294$

$u_I = .00862$

$u_t = .00130$

$m = X$

$c T_f + h_f = Y$

$V \cdot I \cdot t = Z$

$Y = 4.2 \frac{J}{g°C} (91.6°C) + 334 \frac{J}{g} = 718.72 \frac{J}{g}$

$Z = 17.0V \cdot 5.8A \cdot 384\,min \cdot \frac{60s}{min} = 227{,}000\,J$

$$u_Z = \sqrt{u_V^2 + u_I^2 + u_t^2} = \sqrt{(.00294)^2 + (.00862)^2 + (.0273)^2}$$

$$u_Z = .0288$$

$$Q = c \cdot T_R \cdot = \frac{4.2\ J}{g°c} \cdot 91.6°c = 384.72 \frac{J}{g}$$

$$U_Q = 4.2 \frac{J}{g°c} \cdot U_T = 4.2 \frac{J}{g°c} \cdot 2.5°c = 10.5 \frac{J}{g}$$

$$u_Q = \frac{U_Q}{Q} = \frac{10.5 \frac{J}{g}}{384.72 \frac{J}{g}} = .0273$$

$$Y = Q + h_f$$

$$U_Y = \sqrt{U_Q^2 + \cancel{U_{h_f}^2}} = U_Q = 10.5 \frac{J}{g}$$

$$u_Y = \frac{U_Y}{Y} = \frac{10.5 \frac{J}{g}}{718.72 \frac{J}{g}} = .0139$$

$$u_X = u_m = 4.125 \times 10^{-4}$$

$$U_R = |R| \cdot \sqrt{u_X^2 + u_Y^2 + u_Z^2}$$

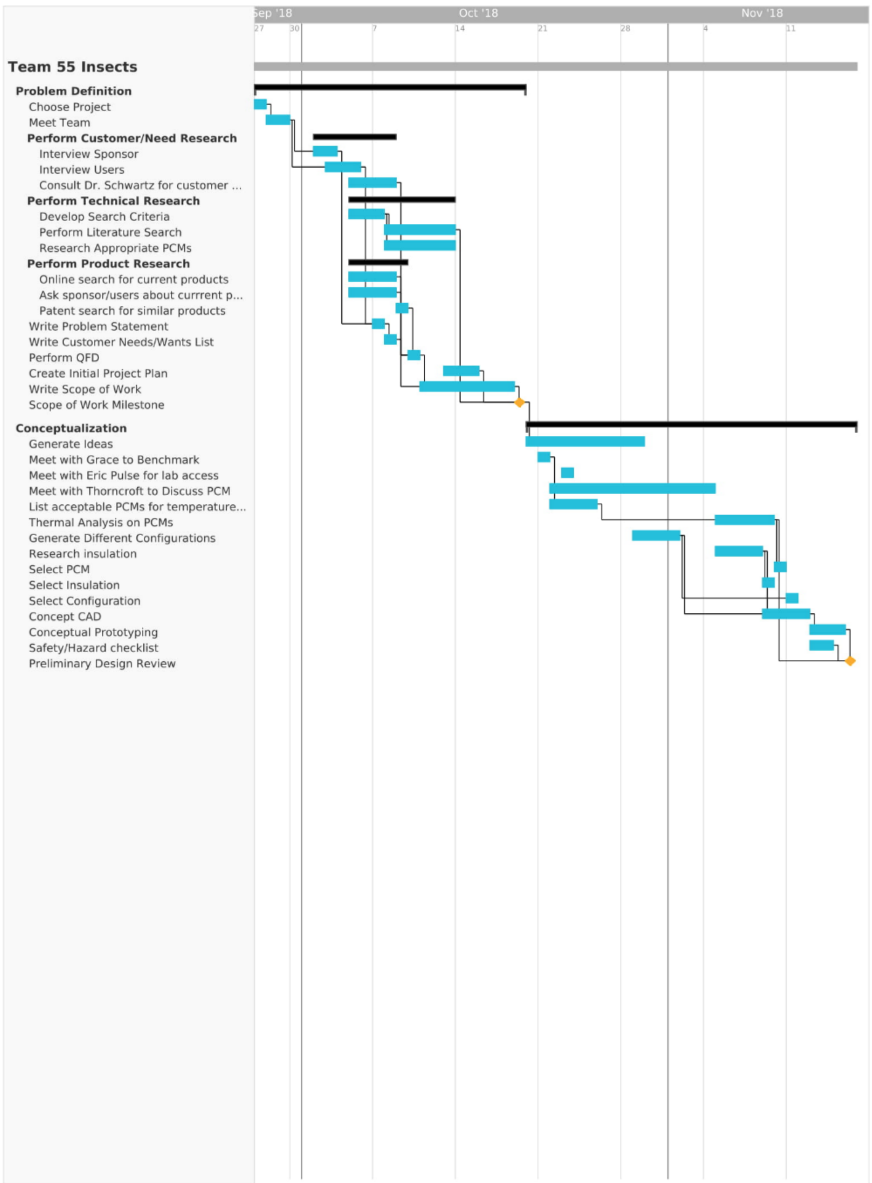
$$U_R = .383 \sqrt{(4.125 \times 10^{-4})^2 + (.0139)^2 + (.0288)^2}$$

$$U_R = .013$$

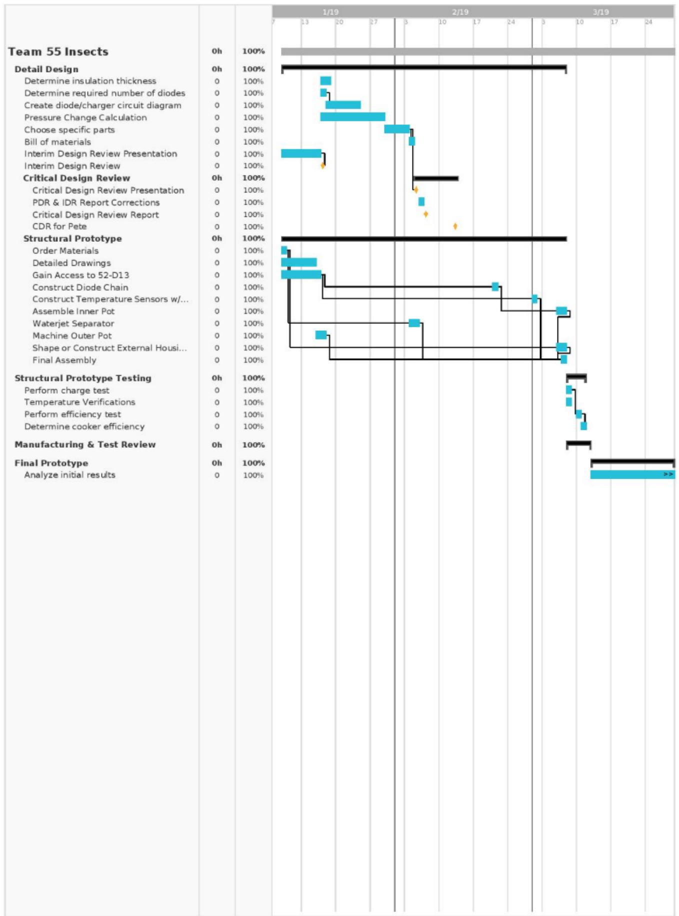
$$\boxed{\begin{gathered}\eta = .383 \pm .013 \\ 38.3\% \pm 1.3\%\end{gathered}}$$

Appendix W: Gantt Chart

1st Quarter Gantt



2nd Quarter Gantt



3rd Quarter Gantt